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# STRUCTURAL INTEGRITY INVESTIGATIONS OF FEEDER PIPE ICE PLUGGING PROCEDURES

Report No 84-462-K

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Mechanical Research Department

## ABSTRACT

A procedure involving the use of a liquid nitrogen cooled heat exchanger to form internal ice plugs in feeder pipes is routinely used in nuclear generating stations. The use of this procedure has caused concerns with regard to the safety of station maintenance personnel, and in regard to the integrity of the feeder pipes. This report describes the results of laboratory stress and pressure measurements which were performed on a feeder pipe section during ice plugging operations to investigate these concerns. From the results of this study, and from the results of previous studies of material behaviour at low temperatures, it has been determined that the ice plugging procedure can be performed on feeder pipes in a safe and effective manner.



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EXECUTIVE SUMMARY

# STRUCTURAL INTEGRITY INVESTIGATION OF FEEDER PIPE ICE PLUGGING PROCEDURES

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A routine procedure in nuclear generating stations involves the creation of internal ice plugs in feeder pipes to temporarily isolate fuel channels. In this procedure a heat exchanger is located around the water-filled pipe at the position where the blockage is to be made. Then, the heat exchanger (or "jacket") is filled with liquid nitrogen (-196°C) causing heat to be removed from the pipe and an ice plug to form.

Based upon the significant reduction in fracture toughness of the feeder pipe steel at low temperatures, it was determined that even very small flaws in the pipe could result in a catastrophic pipe failure, due to high stresses which were thought possible to occur during ice plugging. This report investigated structural concerns of the ice plugging procedures through the performance of tests involving the measurements of stresses, temperatures, pressures and forces relating to the integrity of the pipe and of the ice plug.

From the results of this study combined with materials behaviour data, it has been determined that:

1. Maximum tensile stresses in feeder pipes due to the ice plugging procedure are not excessive in relation to permissible flaw sizes and material behaviour at low temperatures.

2. The ice plugging procedure can be safely performed with little possibility of immediate or delayed damage to the feeder pipe.

3. Properly formed ice plugs can safely resist high differential water pressures with negligible chance of water leakage past the plug or of plug slippage.

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Manager - Nuclear Systems Dept
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# STRUCTURAL INTEGRITY INVESTIGATIONS OF ICE PLUGGING PROCEDURES ON FEEDER PIPES

## 1.0 BACKGROUND

In nuclear generating stations, a routine procedure to temporarily block water filled feeder pipes involves the formation of an internal ice plug. In this procedure, an annular jacket is placed around the pipe, and the jacket is then filled with liquid nitrogen (-196°C). The removal of heat from the pipe at the location of the jacket causes a solid ice plug to form within the pipe.

Due to the possibility of high stresses which may arise in the pipe steel during the plugging procedure, combined with the existence of material flaws and the reduction in fracture toughness of the feeder pipe material at liquid nitrogen temperatures, concerns have been expressed as to the safety of the ice plugging procedure.

These concerns relate to: the capability of the pipe to accommodate the thermal and mechanical stresses caused by the temperature changes of the pipe and the interaction with the ice plug; the long-term serviceability of the pipe due to possible undetected damage incurred during ice plugging; and; the ability of the ice plug to resist leaking or dislodging due to hydrostatic pressure.

A series of laboratory experiments were recently carried out on an instrumented feeder pipe to document various physical phenomena which relate to the safety of this procedure for routine nuclear plant maintenance requirements.

## 2.0 TEST APPARATUS

A 2 m long 3.5 inch feeder pipe section from Bruce NGS 'A' was obtained for testing requirements. One end cap was welded to the bottom of the pipe while the top was left uncapped. (The

pipe was in the vertical position for all tests). Special cryogenic strain gauges and temperature sensors/1/ were attached to the external surface of the pipe at various locations, as shown in Figure 1 on the following page. A single wall ice plugging jacket was positioned at about mid-section of the pipe. As such, some of the strain gauges were within the boundary of the jacket (exposed directly to the liquid nitrogen) while other gauges were located at various positions below the jacket location.

At the bottom of the pipe, a tap was located to provide a hydraulic connection to the water within the pipe. (For some tests, an electronic pressure gauge was attached to monitor increases in water pressue due to the ice plug formation. For other tests, a "manometer" line was connected to this tap to maintain water level within the pipe, and to ensure that water pressure in the lower part of the pipe could not increase during the formation of the ice plug).

All instrumentation was connected to a computer-controlled data acquisition system. Extensive calibration tests were performed before actual testing to verify that all measurement equipment was functioning properly. When all aspects of the measurement equipment were fully demonstrated to be accurate and reliable/2,3/, the tests were peformed. Pictures of the test apparatus are shown in Figure 2 on page 4.

## 3.0 TEST RESULTS

### 3.1 Ice Plugging With No Fluid Pressure Increase

In the first series of tests, the "manometer" was attached to the bottom of the pipe and no pressure boundaries were located at either the top of the pipe or the top of the manometer water line. This ensured that no fluid pressure (other than a hydrostatic head of about 2 m) could build up at the bottom of the pipe during the formation or melting of the ice plug.

As such, these tests were to investigate the increase in stress in the outside surface of the pipe due to the combination of pipe thermal stresses and mechanical interaction stresses caused by the formation/melting of the ice plug.

Of immediate interest are the stresses at the specific strain gauge location which indicated the maximum tensile stress changes. This location was inside the cooling jacket within about 10 mm of the lower boundary of the jacket (Location #3). In this area, the exterior surface of the pipe is in direct contact with the liquid nitrogen.

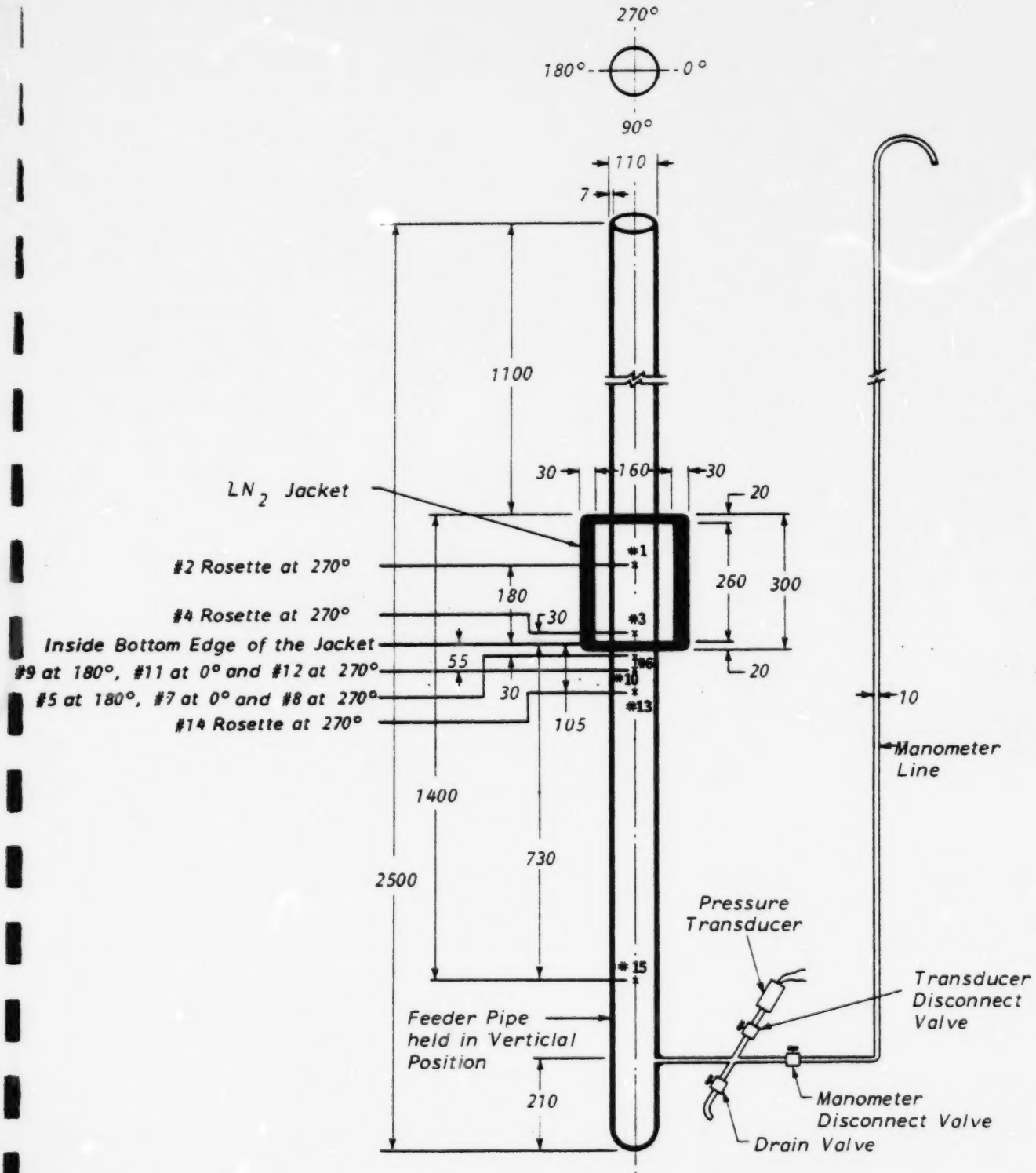


FIGURE 1

LOCATION OF STRAIN GAUCES/TEMPERATURE SENSORS ON FEEDER PIPE TEST SECTION



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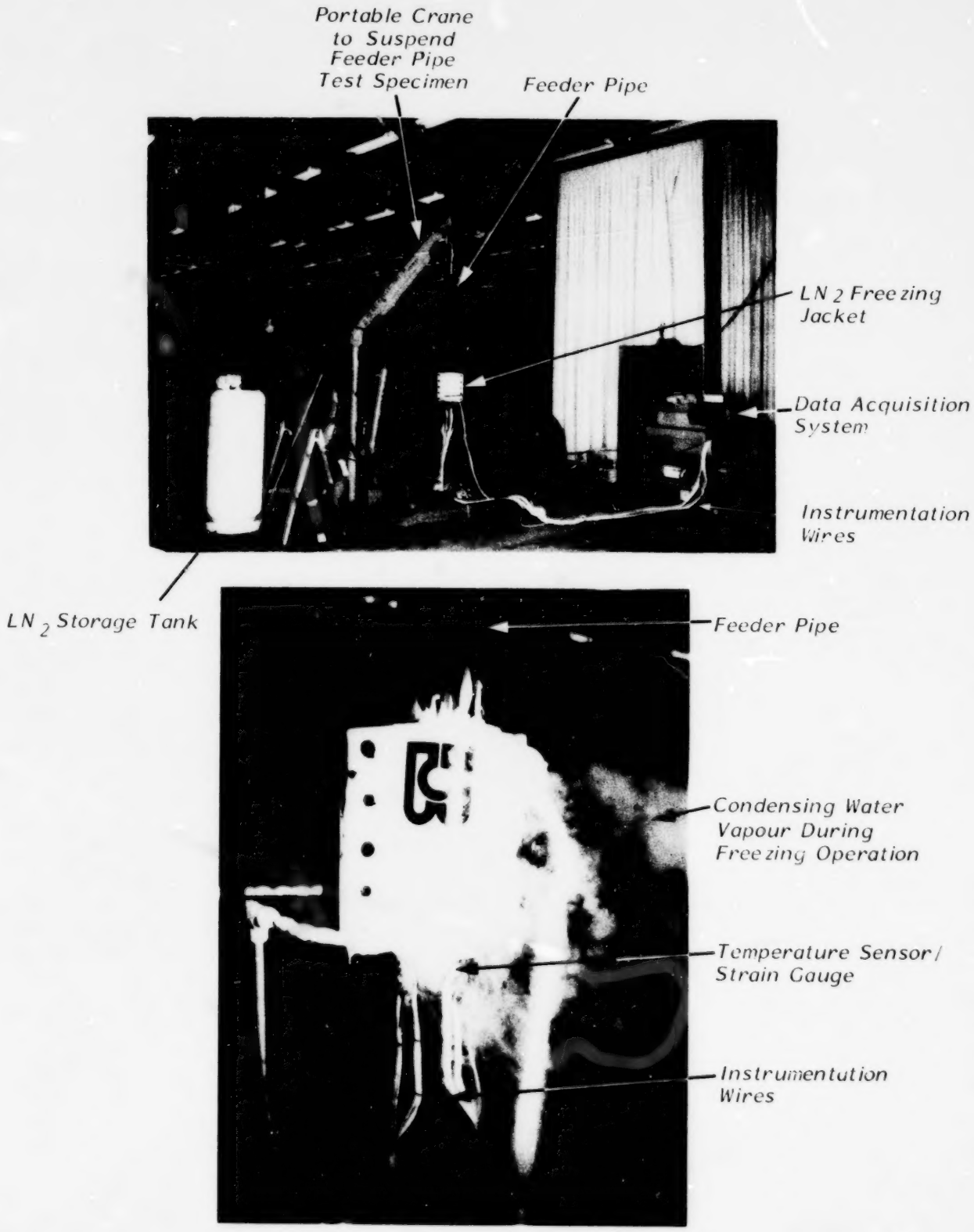



FIGURE 2
PICTURES OF THE TEST APPARATUS

Shown on the following page (in Figure 3) is the entire history (stress vs time) of the stress changes at highest recorded stress location during both plug formation and during plug melting.

Within a short time of introducing the liquid nitrogen into the jacket, the material on the external surface became stressed in tension to about 100 MPa. (The yield strength of the pipe at room temperature is greater than 400 MPa; near liquid nitrogen temperatures, the yield stress would exceed 1000 MPa). This value of 100 MPa is the maximum tensile stress for this test[1] that was experienced at this location during the entire formation and melting of the ice plug. This maximum tensile stress at this location occurred at a temperature of about -150°C. Complete stress vs temperature data for this strain gauge position is shown in Figure 4 on page 7.

After reaching this peak magnitude, the stress at this rosette position quickly dropped to very low levels and never subsequently exceeded 20 MPa during the remaining formation or melting of the ice plug.

Entire graphs for all rosette positions are included for this test in Appendix 'A'. This appendix includes graphs of "stress vs time", "stress vs temperature" and "temperature vs time" for all strain gauge rosette positions.

In general, the following have been observed for these tests:

1) Maximum pipe stresses are tensile, occur close to the boundary of the jacket, and always occur during ice plug formation.

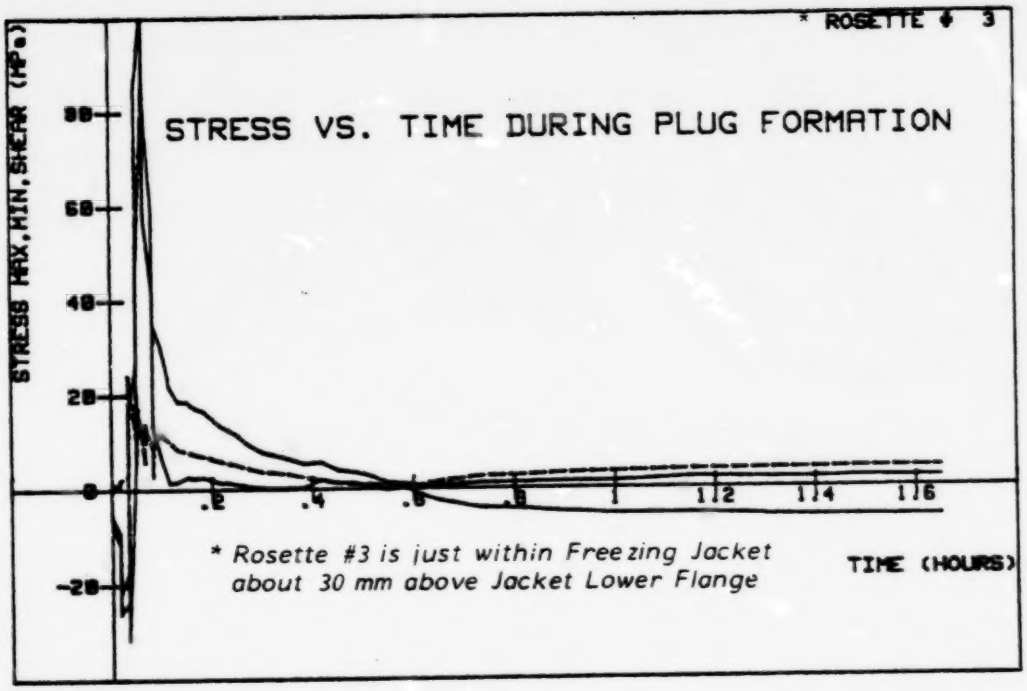
2) Stresses are higher within the jacket than areas outside of the jacket.

3) During plug formation, the rise of the maximum stress at each rosette position occurs sequentially with time (as the plug "grows" past each rosette).

4) The rate of stress increase or decrease at any point on the pipe is generally proportional to the proximity of the point to the jacket flanges.

---

[1] The maximum stress changes varied from test to test by as much as 50 MPa, even for nominally identical test conditions. Therefore, it is statistically possible that somwhat higher stresses could occur at this location if many more tests were performed.



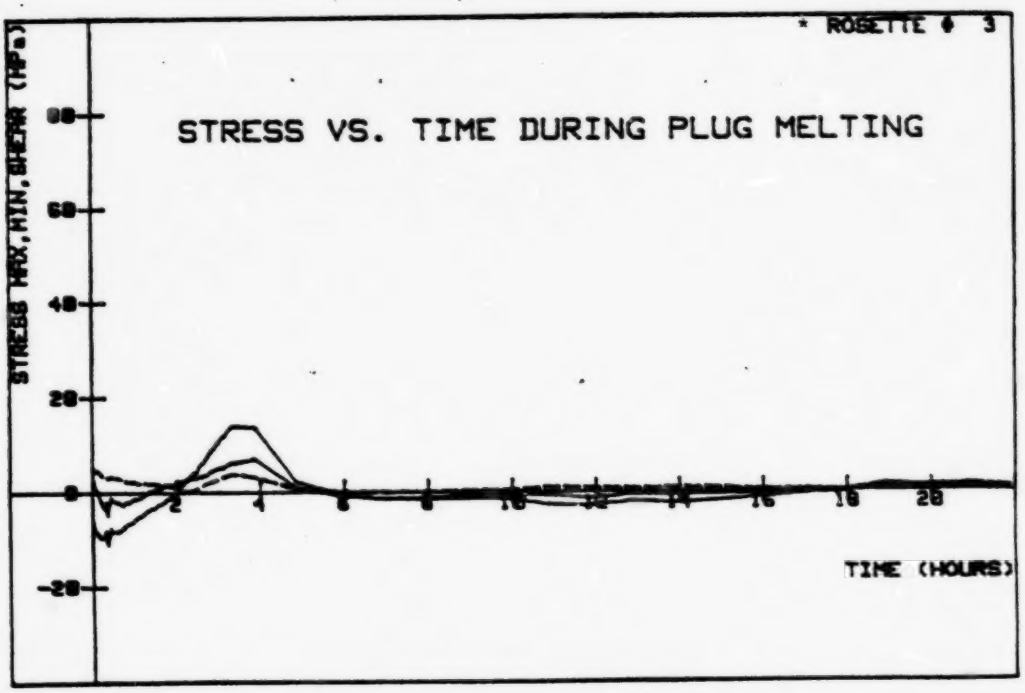
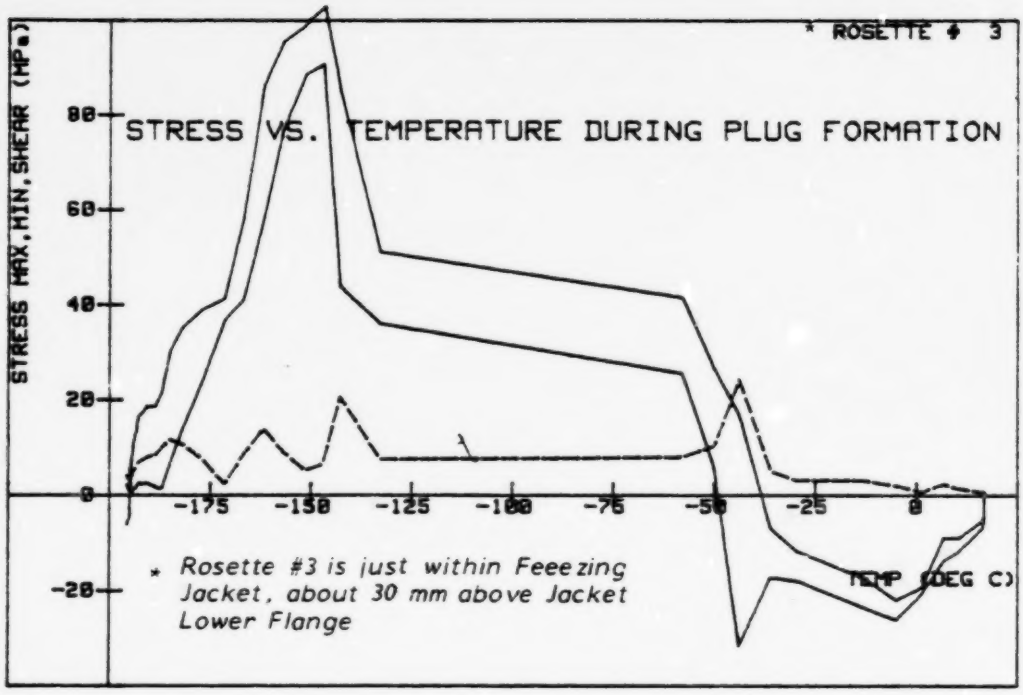




FIGURE 3

STRESS VS TIME AT MAXIMUM STRESS LOCATION
(NO WATER PRESSURE ALLOWED TO BUILD UP IN TEST PIPE)



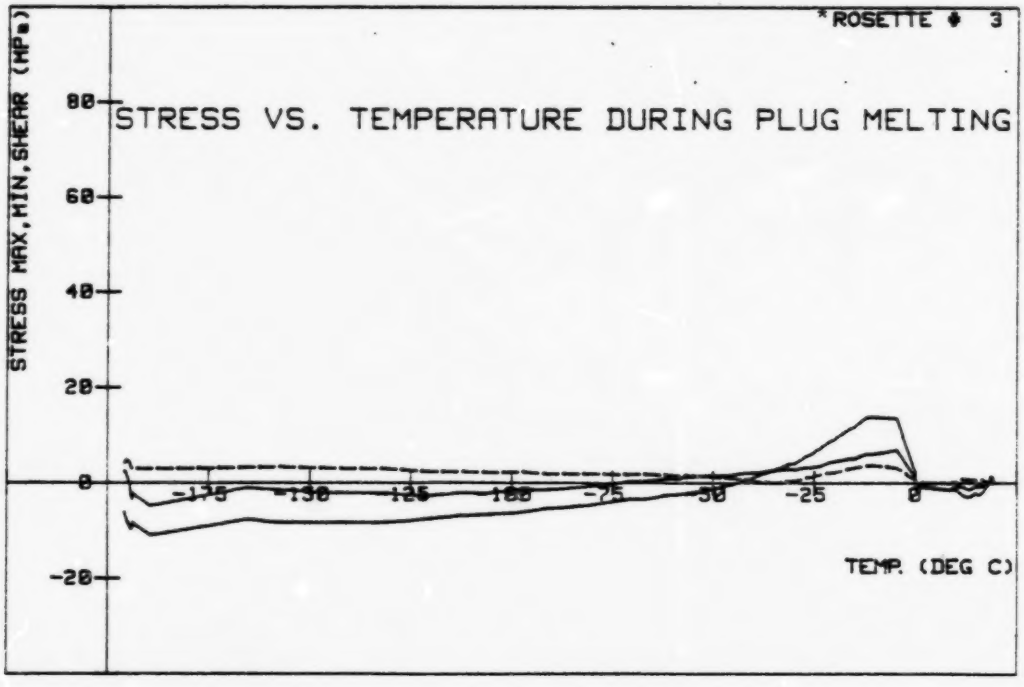




FIGURE 4

STRESS VS TEMPERATURE AT MAXIMUM STRESS LOCATION
(NO WATER PRESSURE ALLOWED TO BUILD UP IN TEST PIPE)

5) During ice plug melting, low compressive stress magnitudes (< 50 MPa) would generally occur at each measurement position.

6) From an analysis at a number of nominally identical tests, there is a significant variability in stress changes (±50 MPa) from test to test, and from one rosette location to another rosette location on the same circumference.

### 3.2 Stress Changes at Each Measurement Position Due to Subsequent Pressurization Against Fully Formed Ice Plug

At the completion of a fully formed ice plug (at which time strains and temperatures were seen to stabilize at all rosette positions) a simulation of a station hydrostatic test was performed to observe the stress changes in the pipe due to this procedure. (This test would also simulate the reduction of pressure on one side of the ice plug which was initially formed in a pressurized pipe).

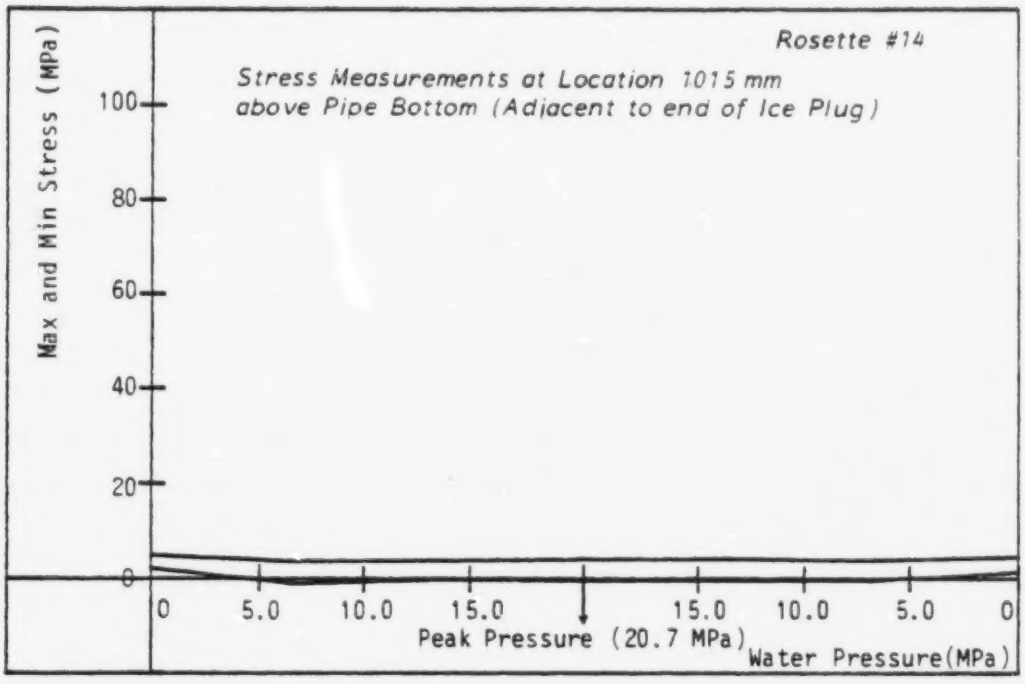
In this test, fluid pressure was increased in increments of about 7 MPa using a manual pump connected to the tap at the bottom of the pipe. The only stress changes that were detected were from the rosette at the extreme bottom of the pipe (where the water was always in the liquid state). These stress changes (for Rosette 15) are shown in Figure 5 on the next page and are precisely equal to the stresses that would be produced from purely fluid pressure effects. No stress changes were observed at any of the other rosette positions as shown for the next rosette nearest the pipe bottom, Rosette 14. (This rosette (#14) "covers" the ice plug).

### 3.3 "Trapped" Water Pressure Increase Due to Ice Plug Formation

In this test, the tap on the bottom of the pipe was closed. A pressure gauge, however, was connected hydraulically to the pipe to record changes in fluid pressure due to plug formation and melting. A graph of the pressure increase vs time is shown in Figure 6.

This test would simulate the situation where an ice plug was formed near a closed valve or near a previously formed ice plug.

The maximum stresses at all locations covering the ice plug were not significantly different in this test from the previous test in which there was no fluid pressure increase. As shown in Figure 1, on page 3, nearly all of the strain gauges are located in the area of the ice plugging device.



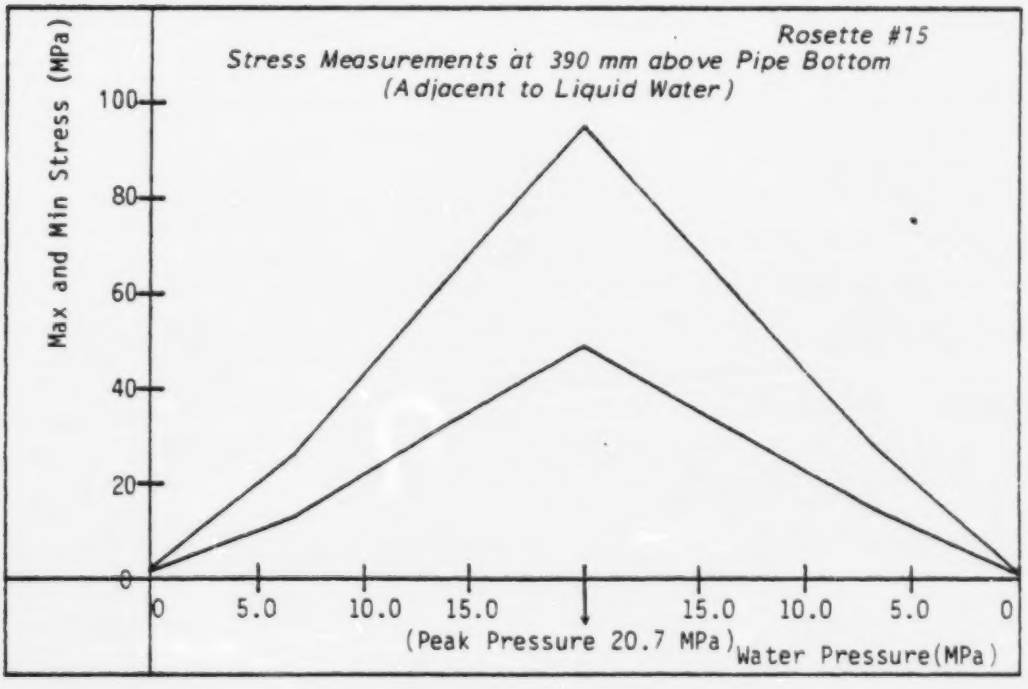
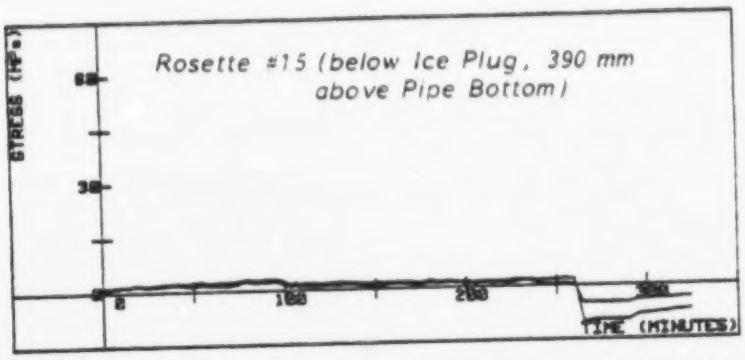



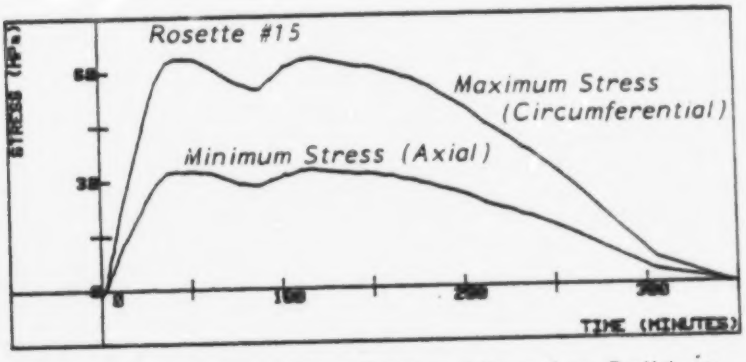

FIGURE 5

STRESS MEASUREMENTS DUE TO HYDROSTATIC PRESSURE TESTS
AGAINST FULLY FORMED ICE PLUG



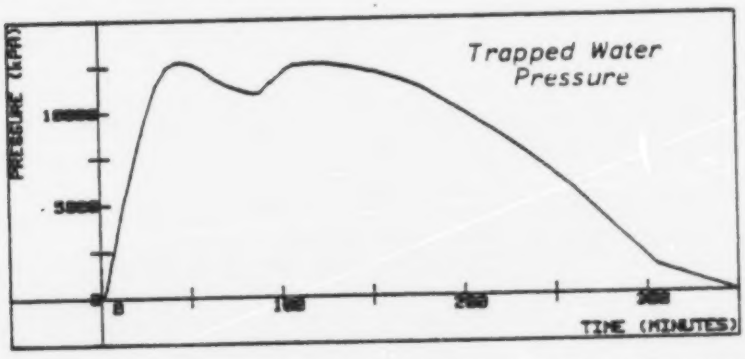

"TEST 6"

Water Pressure at Pipe Bottom Not Allowed to Increase During Plug Formation (Manometer Used)




"TEST 7"

Water Pressure at Pipe Bottom Allowed to Build up During Plug Formation (Bottom Valve Closed)




"TEST 7"

Pressure Changes at Pipe Bottom During Plug Formation Due to "Trapped" Water (Test 7)

FIGURE 6

STRESS/PRESSURE CHANGES DUE TO "TRAPPED" WATER DURING ICE PLUG FORMATION

The only major difference in maximum stress changes between the test in which there was trapped water and the test where the water pressure was not allowed to increase was for the rosette at the pipe bottom (where ice did not form). Only in this area was there seen to be proportional increases in pipe stresses due to the increases in pressure of the (trapped) fluid.

It should be noted that there was a relatively large column of trapped water below the ice plug. Therefore, it is clear that fluid pressure increases in the trapped water would be higher if the plug had been formed closer to the pipe bottom (ie, if the amount of trapped water were smaller).

### 3.4 Tests to Determine Material Damage Due to Ice Plugging Procedure

Of direct concern to pipe integrity is the possible occurrence of undetected pipe damage during the ice plugging procedure. This damage would be manifested in a permanent change in stress or strain in the pipe material due to the performance of a plugging operation.

If this were to occur on station feeder pipes, then such damage, if severe, might lead to a catastrophic rupture during subsequent unit operation. Additionally, even if such damage is relatively slight, it could be cumulative due to repeated ice plugging operations at the same location. This cumulative damage could lead to a subsequent in-service failure or it could lead to a failure during a subsequent ice plugging operation.

With regard to all of the previous tests, the net change at the strain gauge locations due to the formation and melting of the ice plug was closely monitored. It was observed that no material yielding took place due to any of these previous tests. This indicates that the ice plugging operation could not produce permanent "damage" on feeder pipes. A typical example is the result of one test, shown in Table 1, on page 12.

This result (which shows no net stress changes due to a plugging operation) is consistent with the measurements taken during the plugging procedure. This is because yield stress was never seen to be exceeded during the formation or melting of the ice plug. As such, permanent material deformations would not have been expected to occur from this procedure due to low stress measurements obtained during ice plugging operations.

In these tests, no significant defects existed at the area of the ice plug. From tests and analyses performed elsewhere/6/ it has been determined that there is very little risk of pipe rupture or damage even when "large" and otherwise unacceptable defects might exist in the pipe.

TABLE 1

MAXIMUM AND RESIDUAL STRESS DURING AND AFTER ICE PLUGGING TEST

*(No pressure was allowed to build up in the lower end of the pipe)*

| Rosette No | Stress Before Ice Plugging Test MPa | Maximum stress During Ice Plug Formation & Melting MPa | Remaining Stress After Ice Plug Fully Melted MPa |
|---|---|---|---|
| 1 | 0.00 | 78.05 | -0.07 |
| 2 | 0.00 | 50.68 | -0.76 |
| 3 | 0.00 | 103.42 | 0.62 |
| 4 | 0.00 | 107.56 | -----* |
| 5 | 0.00 | 32.13 | -1.52 |
| 6 | 0.00 | 27.44 | 4.55 |
| 7 | 0.00 | 70.69 | -2.05 |
| 8 | 0.00 | 64.05 | 3.71 |
| 9 | 0.00 | 52.05 | -1.79 |
| 10 | 0.00 | 18.54 | -1.31 |
| 11 | 0.00 | 19.58 | -3.31 |
| 12 | 0.00 | 28.68 | -1.52 |
| 13 | 0.00 | 19.65 | -1.24 |
| 14 | 0.00 | 21.44 | -0.55 |
| 15 | 0.00 | 1.52 | -0.21 |

* Verified Strain Gage Failure

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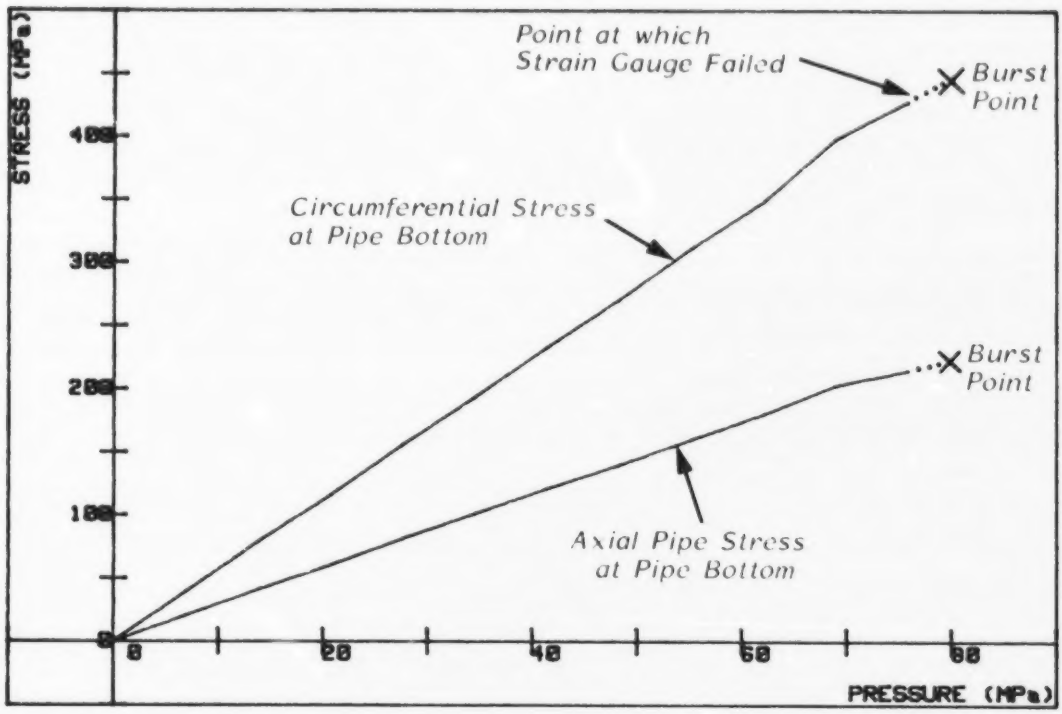
## 3.5 Ice Plug Dislodging Tests

The final test in this study involved an attempt to dislodge the ice plug to determine the general integrity of the plug and to determine a margin of safety during hydrostatic tests.

In this test, an ice plug was allowed to fully form as in the previous tests and then the water pressure at the bottom of the pipe was increased in steps. A graph of fluid pressure vs pipe stress change (at the bottom of the pipe) is shown on the next page in Figure 7.

At about 70 MPa fluid pressure, the strain gauge readings began to deviate from a linear response (to pressure), and this indicated that some material yielding had begun to take place at this pressure. The indicated circumferential pipe stress at this pressure was about 415 MPa.




*Plot of Water Pressure vs Pipe Stress During Ice Plug Dislodging Tests*

*Pressure Tap Location*

*Photograph of Fractured Section of Feeder Pipe due to Pressurization against Ice Plug*

FIGURE 7

RESULTS OF ATTEMPTS TO DISLODGE ICE PLUG

At about 75 MPa fluid pressure, extreme yielding began to occur in the pipe steel as proportionally more fluid was being (manually) pumped into the pipe with relatively small increases in fluid pressure (no fluid leakage was observed from the pipe or test apparatus). The strain gauges failed at this point due to excessive elongation).

At each stage of the testing during pressurization, manual pressurization was halted while the stability of the pressure gauge was observed. At each stage, the pressure was seen to remain steady indicating that:

i) the plug was not slipping; and,
ii) water was not escaping past the ice plug or through faulty pipe fittings or cracks.

At approximately 80 MPa fluid pressure, the pipe suddenly burst. (Normal operating pressure is about 10 MPa). The burst point occurred at the pressure tap locations, near the pipe bottom.

A picture of the burst section (which has been severely deformed) and pressurization data is shown in Figure 7.

## 4.0 DISCUSSION

From all of the tests performed on this feeder pipe, it is clearly indicated that the ice plugging procedure can be performed safely and effectively. However, it must be noted that no parametric studies were performed (on different sizes of pipes, or with various cooling durations, etc). As such the results of these tests must be applied with caution to other ice plugging situations which do not duplicate the test conditions.

However, considering the relatively low magnitude of stresses that were measured in these tests, it is very likely that ice plugging operations can be safely performed in larger or smaller pipe diameters.

The concern regarding the ice plugging procedure involves the combined effects of stress, materials behaviour at low temperature and the occurrence of flaws in the feeder pipe steel. Previous studies/4,5,6/ have shown that because of the relatively low stresses involved with this procedure, there is negligible likelihood that even "large" flaws in service piping will initiate or propogate due to the ice plugging procedure.

## 5.0 CONCLUSIONS

i) Ice plugging operations on feeder pipes can safely be performed (if no fluid pressure increases are allowed to occur).

ii) In constrained conditions, where water can be trapped by the ice plug, the use of the ice plugging procedure can cause excessive pipe stresses to occur.

iii) No permanent pipe damage was detected to result from the ice plugging procedure.

iv) Properly formed ice plugs are shown to easily resist differential fluid pressures equal to the nominal operating pressure of the feeder pipe.

v) Taking into account the low measured stresses, previous studies would indicate that there would be negligible chance of even "large" flaws in feeder pipe propogating due to the ice plugging procedure.

## ACKNOWLEDGEMENTS

We wish to thank Mr. Ivan Pomakov for his assistance in this project and for supplying us with the ice plugging apparatus. Also, we appreciate the efforts and advice of Mr. R. Lyons, and Dr. P.C. Lichtenberger for their support and advice in this project.

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MTF/NNS:ljh

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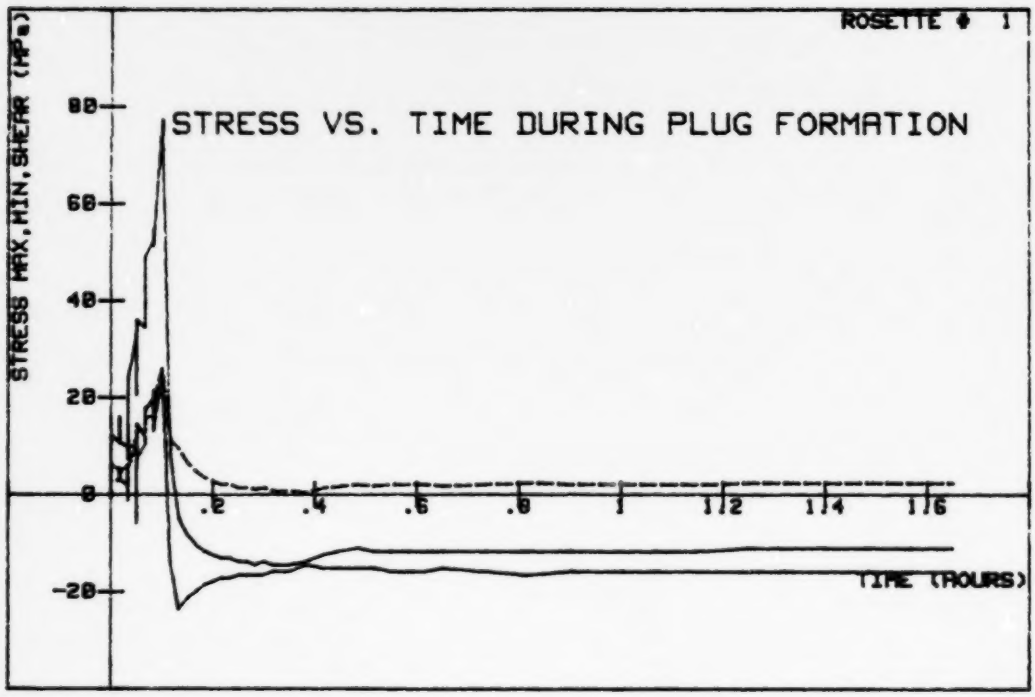
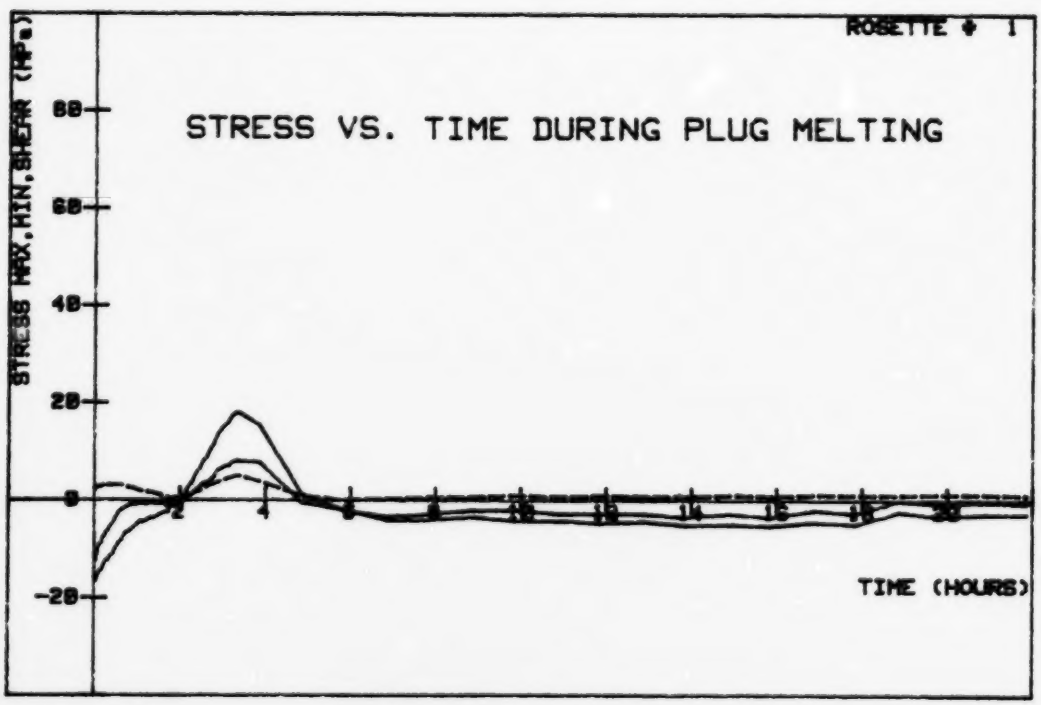
6. "Phase I Development of Guidelines for Use of Ice Plugs in Pipeline Maintenance and Hydrostatuc Testing", November 15, 1982, J.F. Kiefner, et al, Battelle Columbus Laboratories, Columbus, OH.

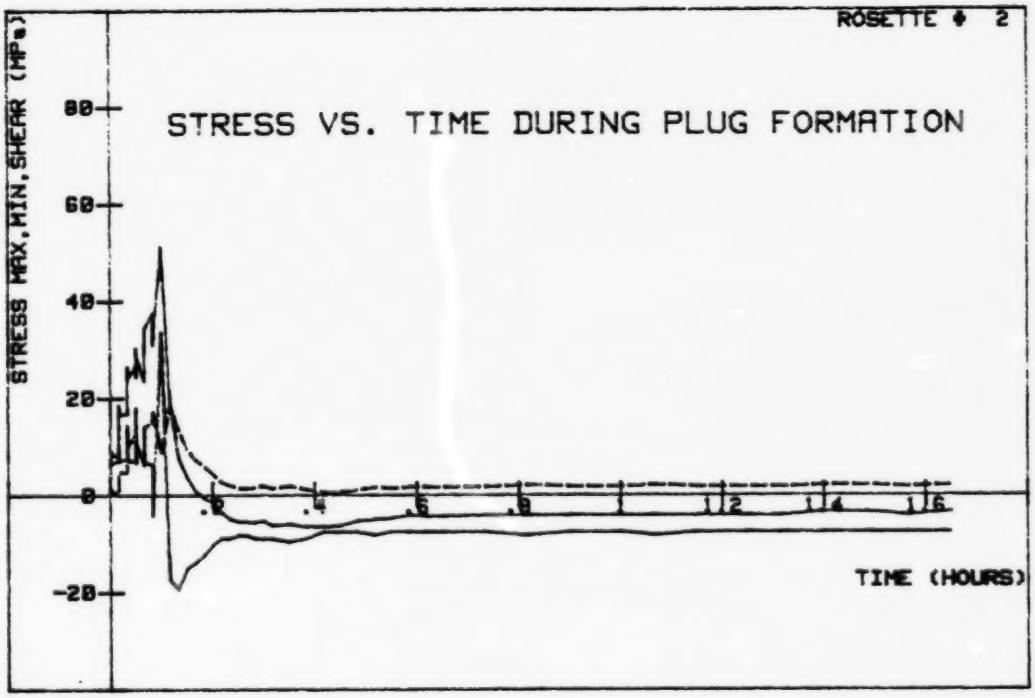
# APPENDIX A

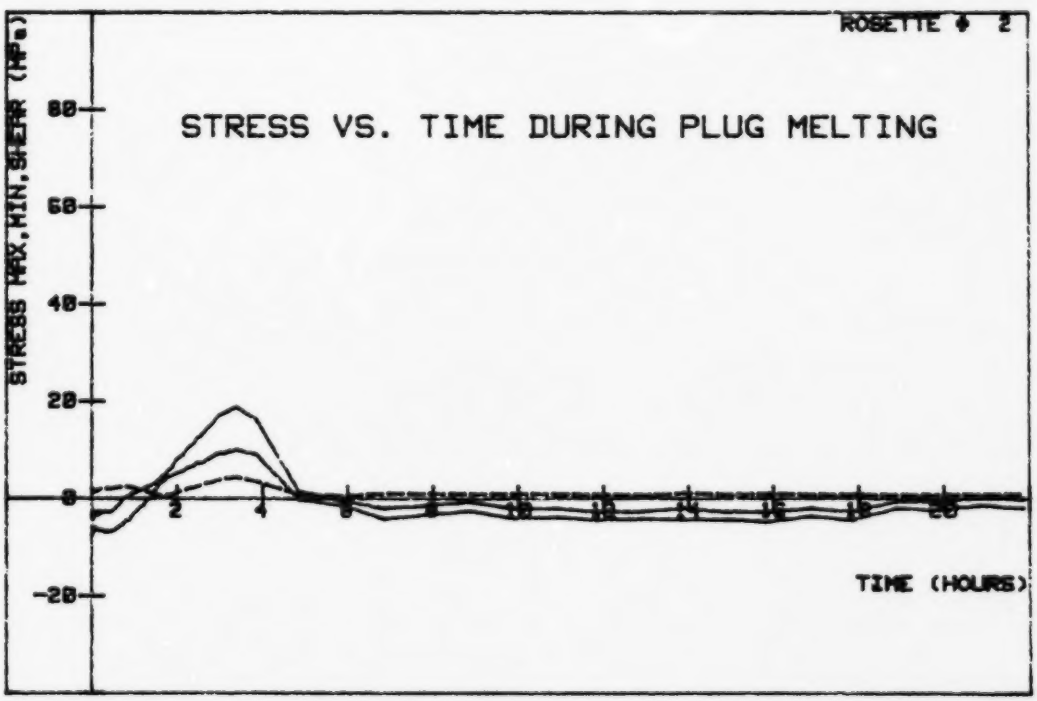
## STRESSES AND TEMPERATURES DURING FORMATION AND MELTING OF ICE PLUG

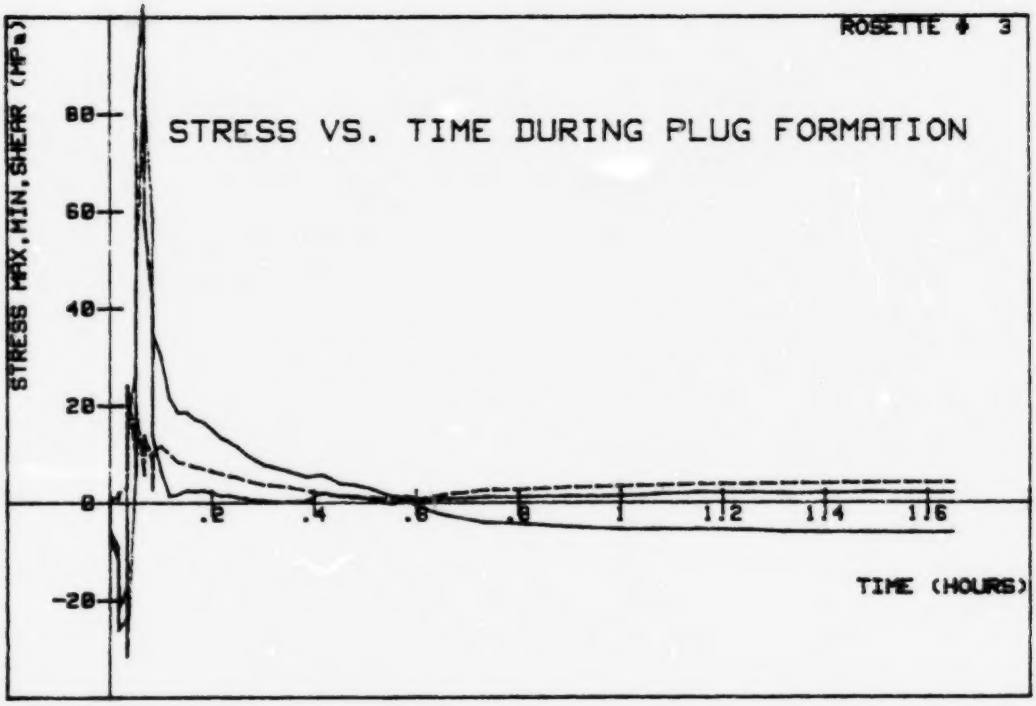
STRESS VS TIME

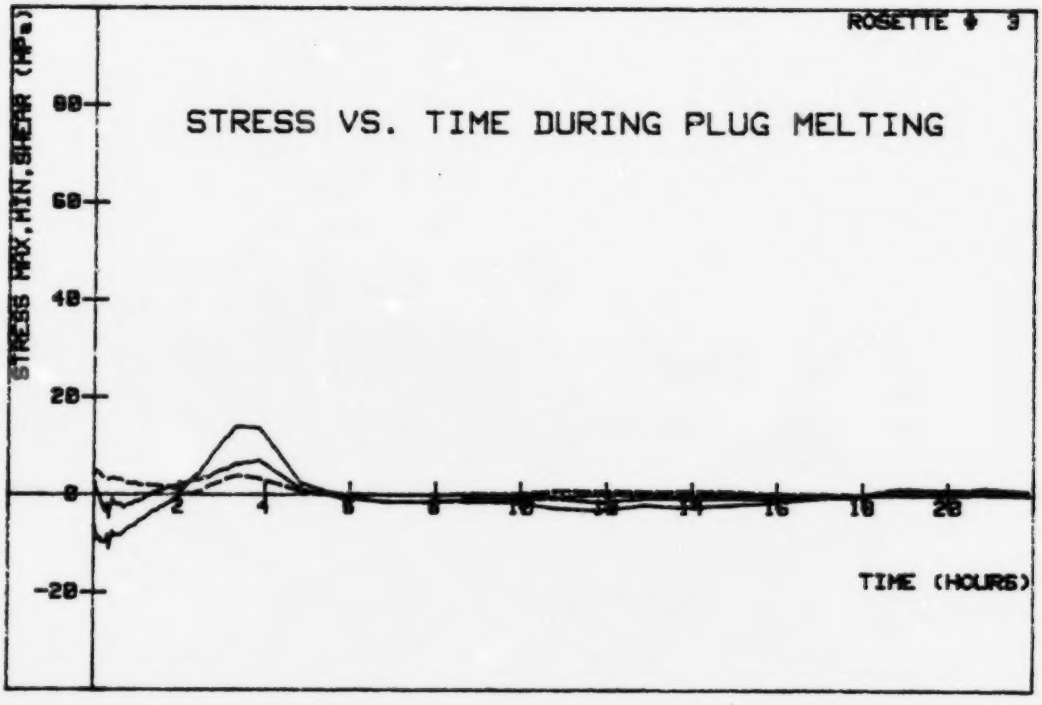

ROSETTE # 1
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

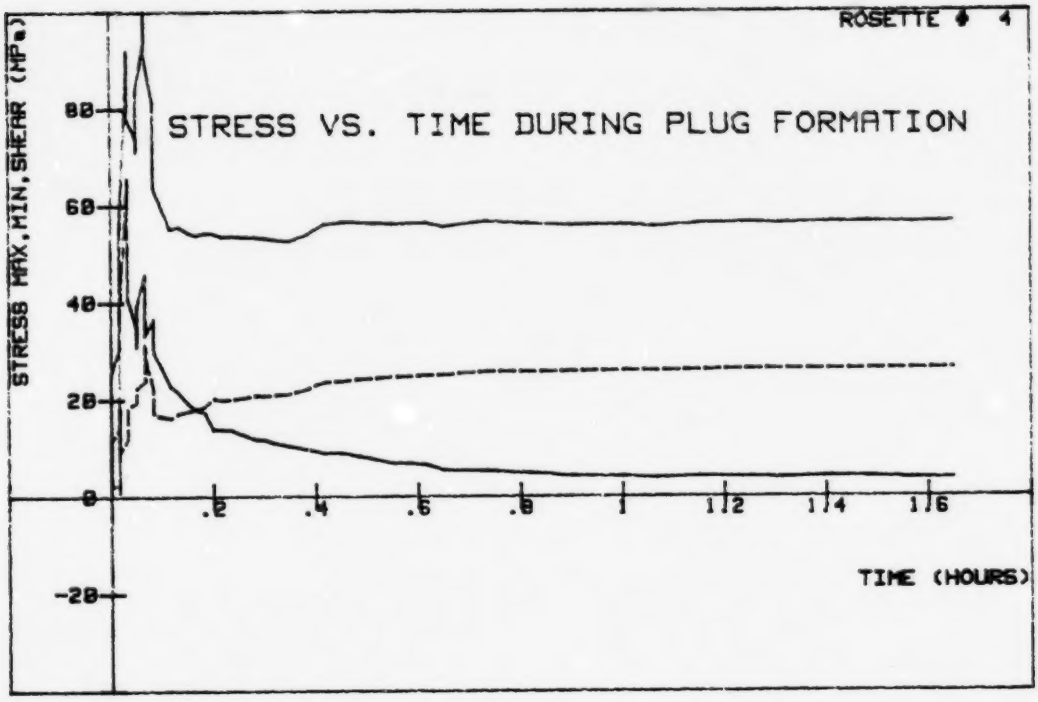

ROSETTE # 1
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
4
TIME (HOURS)

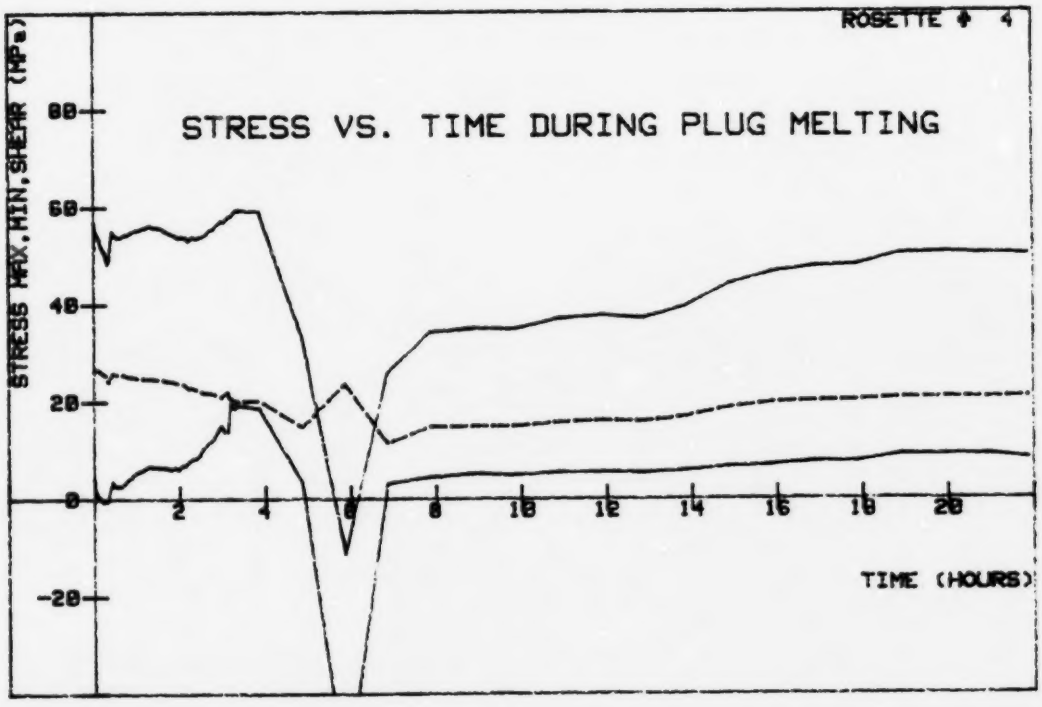

ROSETTE # 2
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX.MIN.SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
2
4
6
TIME (HOURS)

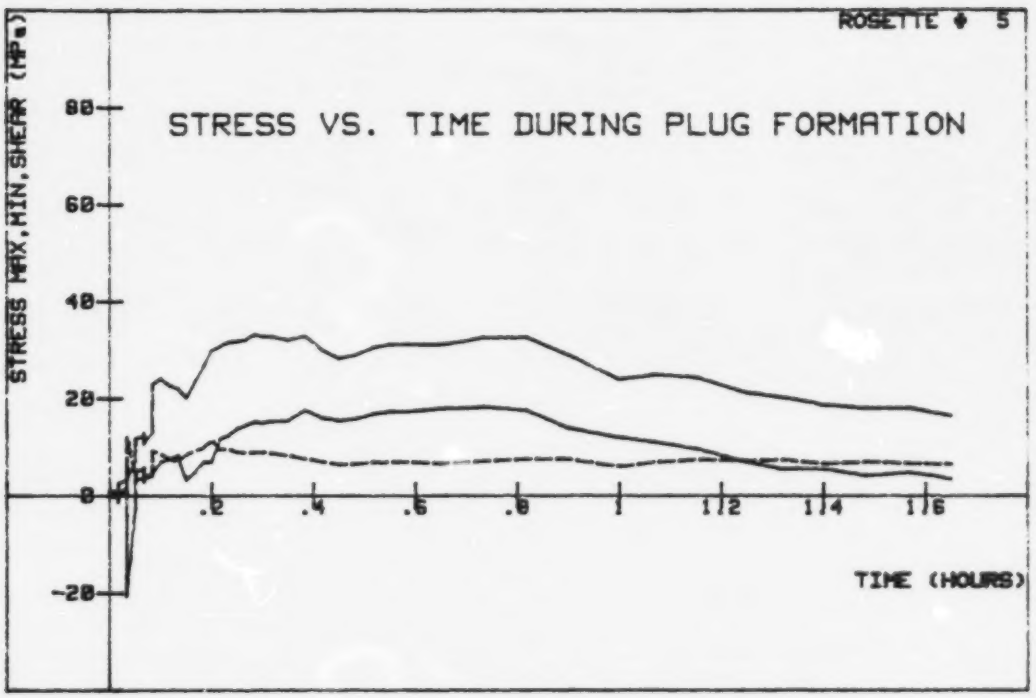

ROSETTE # 2
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX.MIN.SHEAR (MPa)
80
60
40
20
0
-20
2
4
TIME (HOURS)

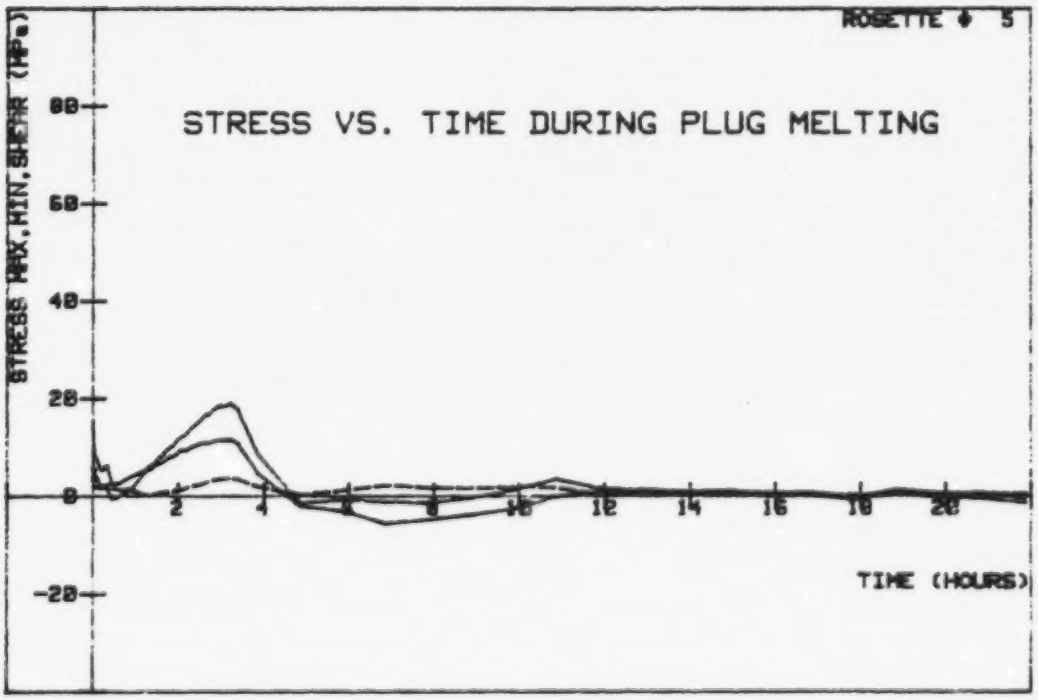

ROSETTE # 3
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

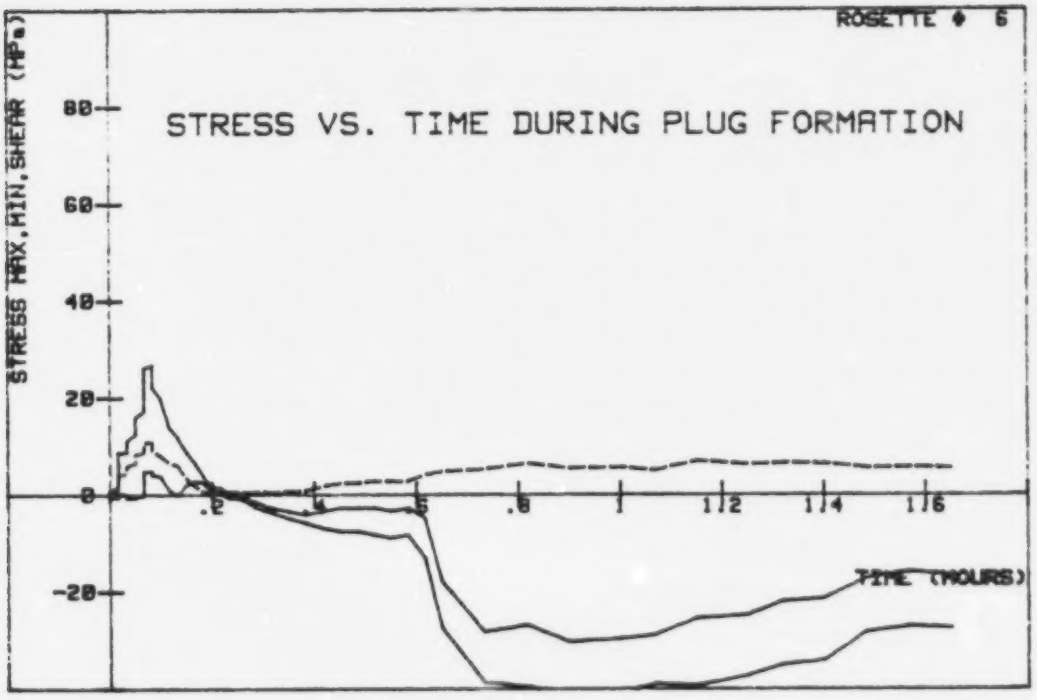

ROSETTE # 3
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

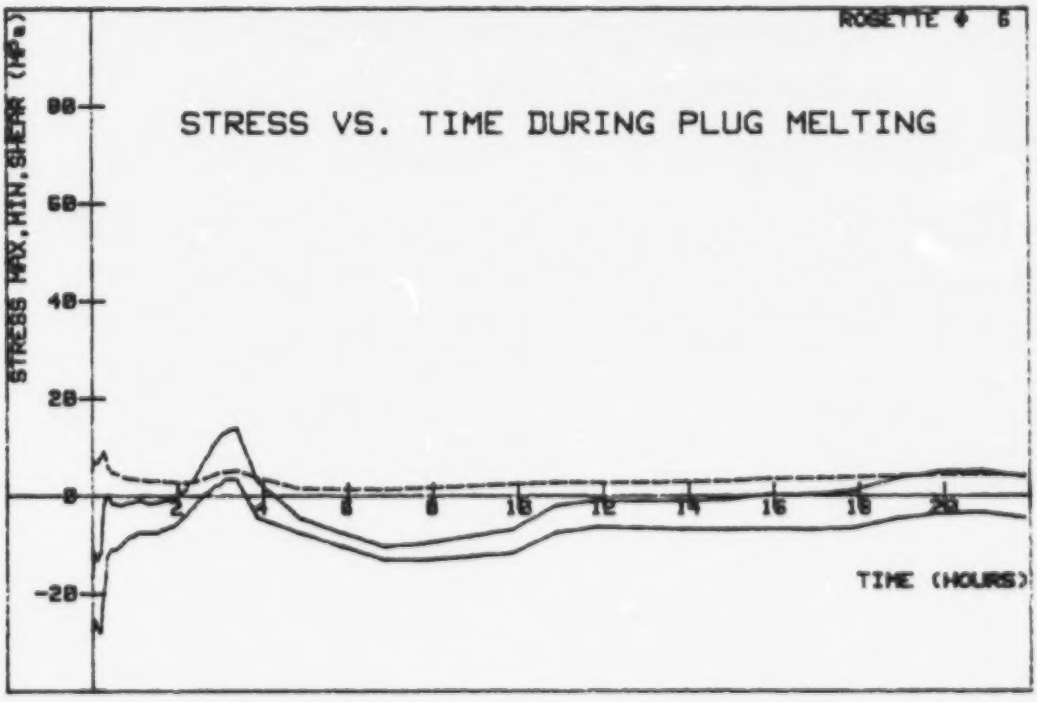

ROSETTE # 4
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1/2
1/4
1/6
TIME (HOURS)

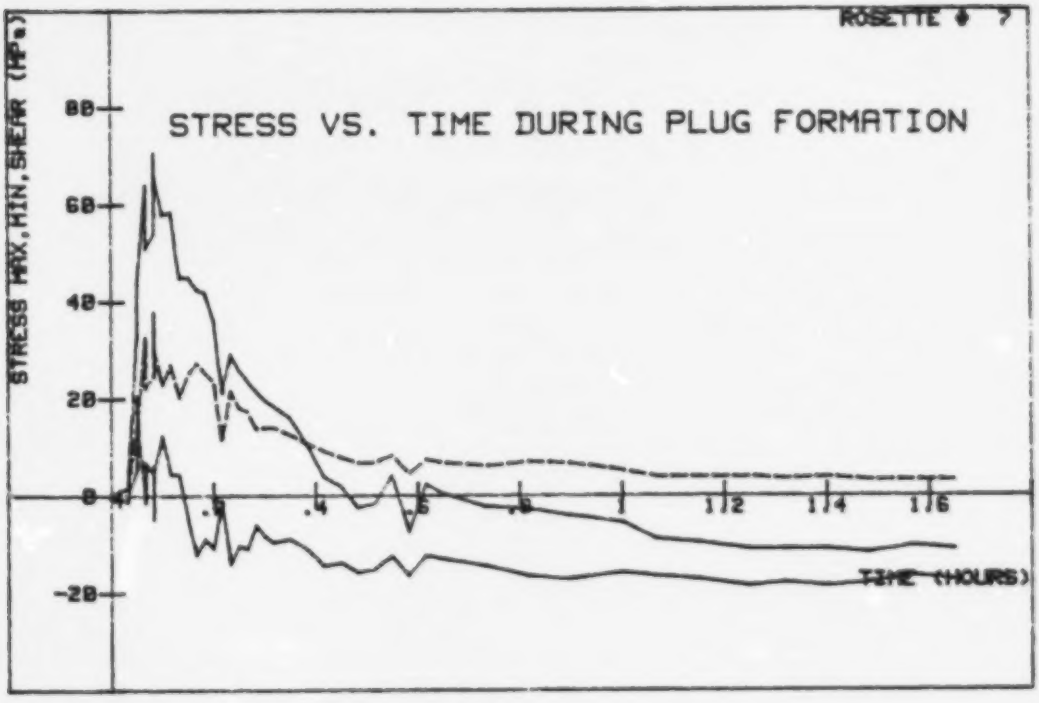

ROSETTE # 4
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

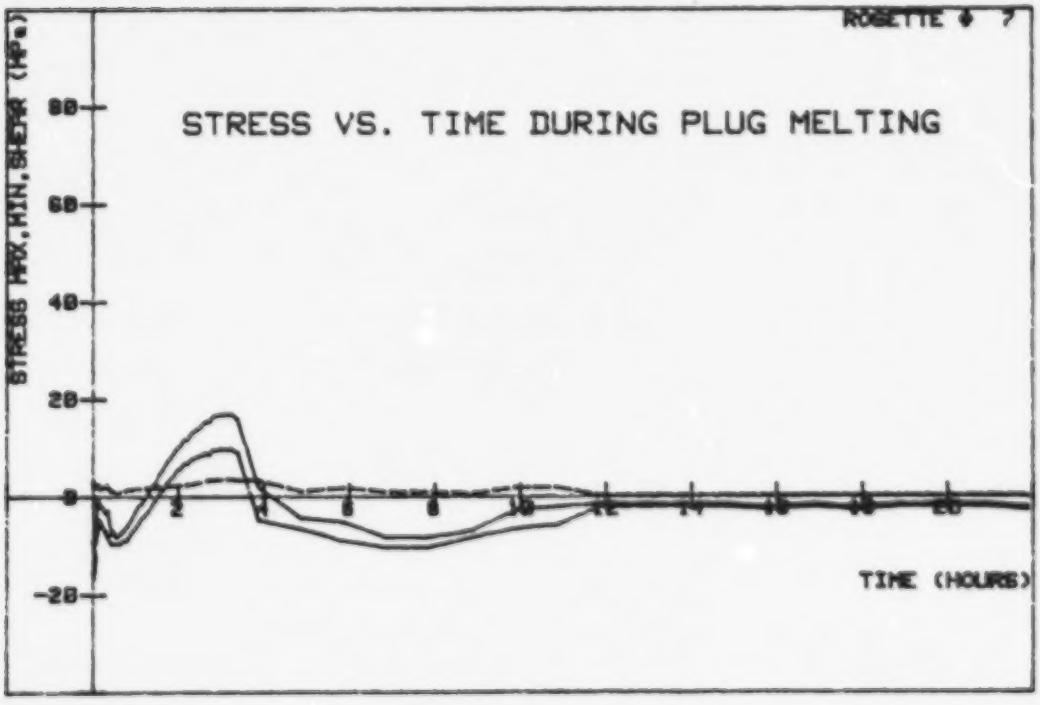

ROSETTE # 5
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1/2
1/4
1/6
TIME (HOURS)

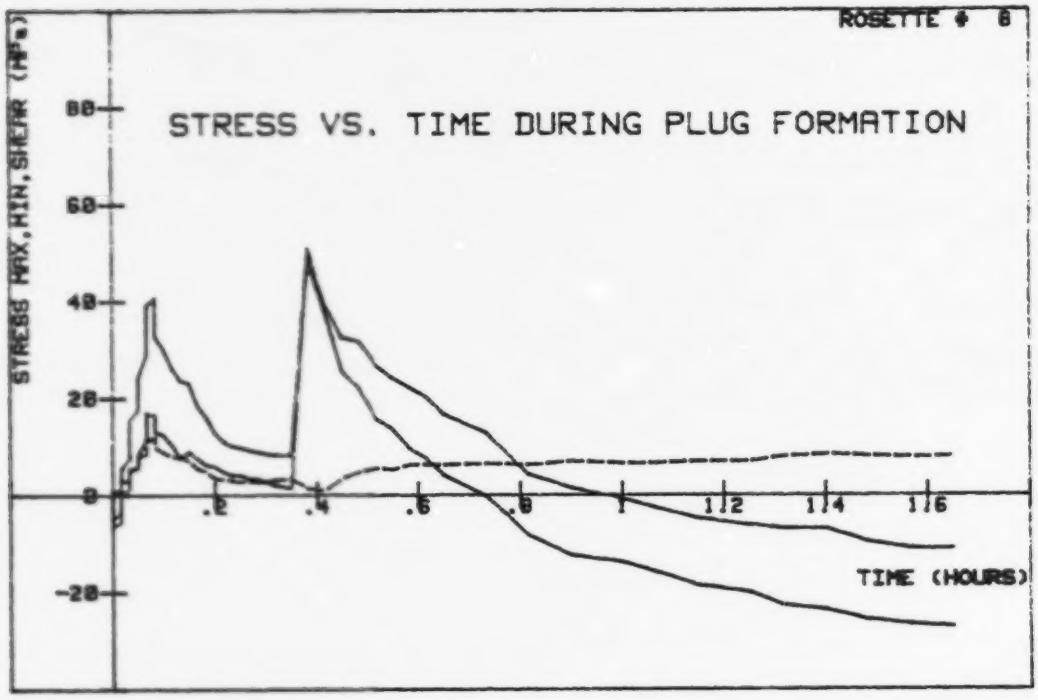

ROSETTE # 5
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

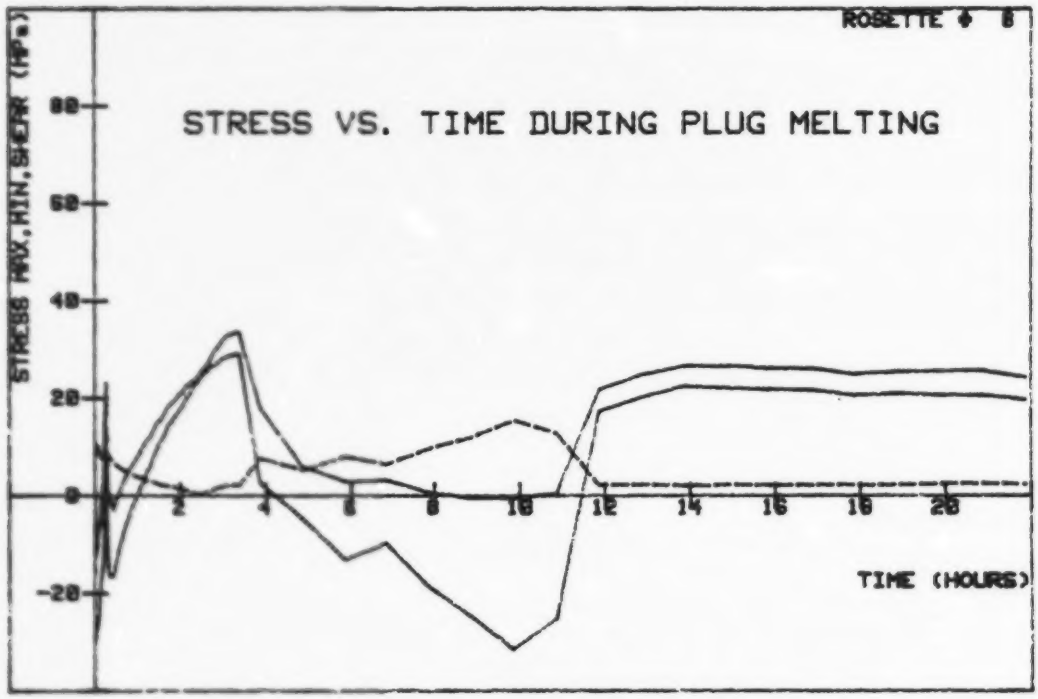

ROSETTE # 6
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1 1/2
1 3/4
2
TIME (HOURS)

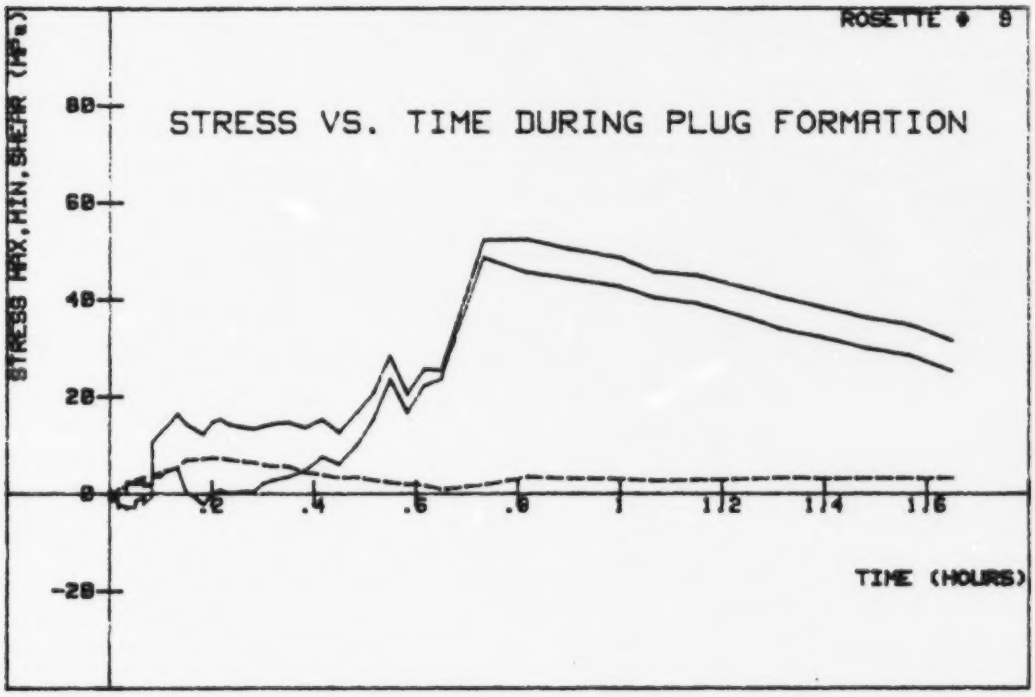

ROSETTE # 6
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

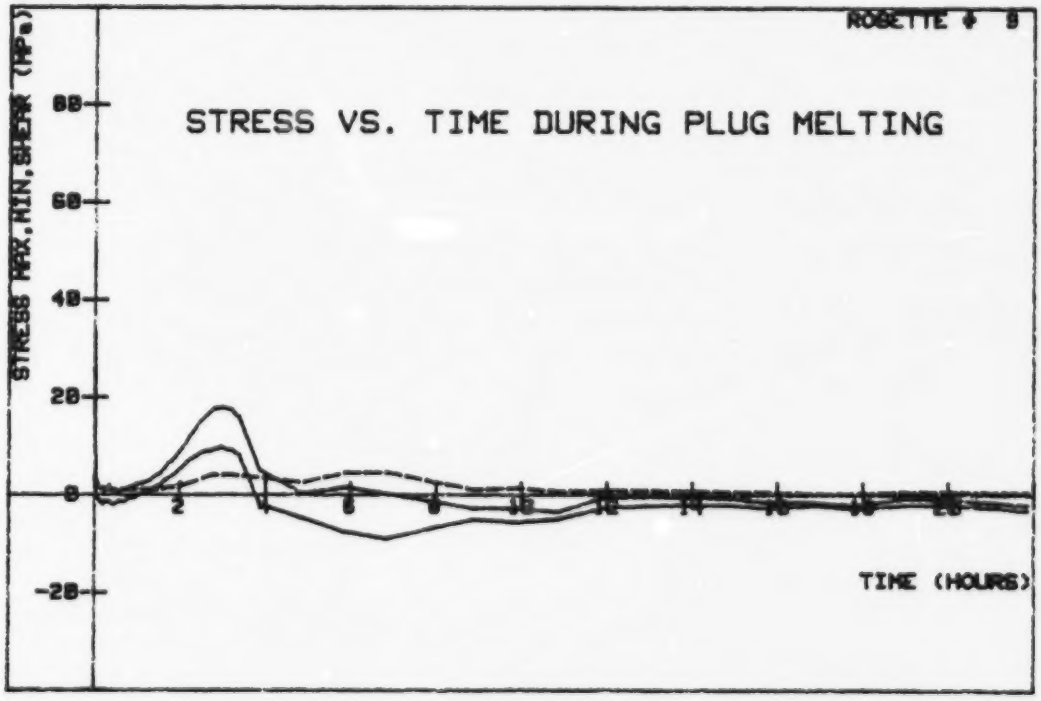

ROSETTE # 7
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
.2
.3
.4
.5
.6
1
1/2
1/4
1/6
TIME (HOURS)

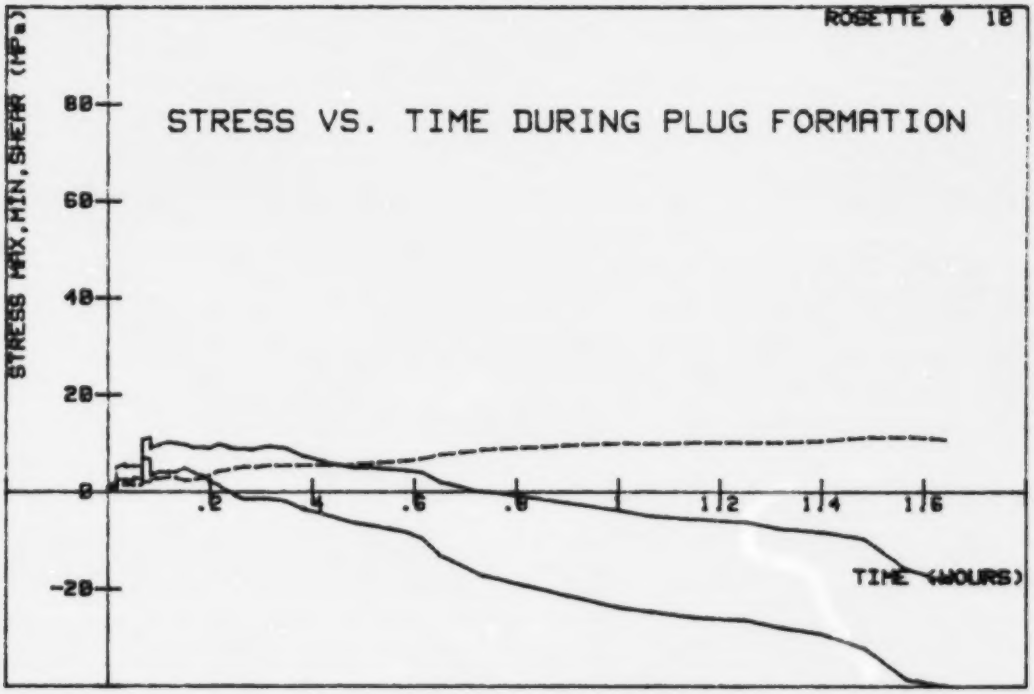

ROSETTE # 7
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

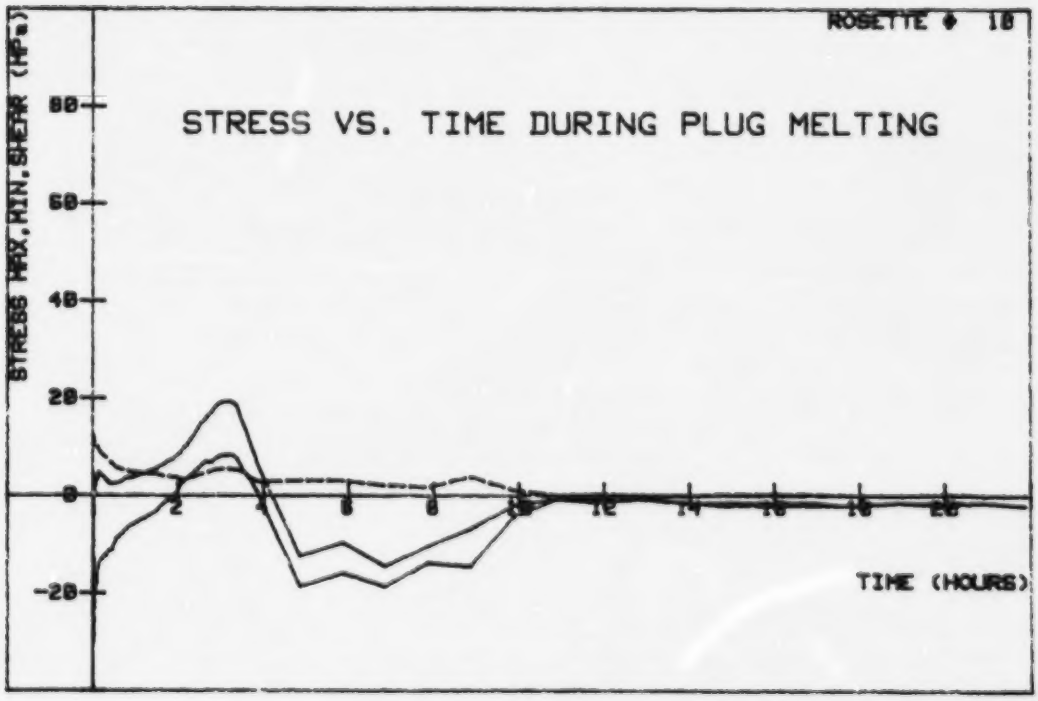

ROSETTE # 8
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX, MIN, SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

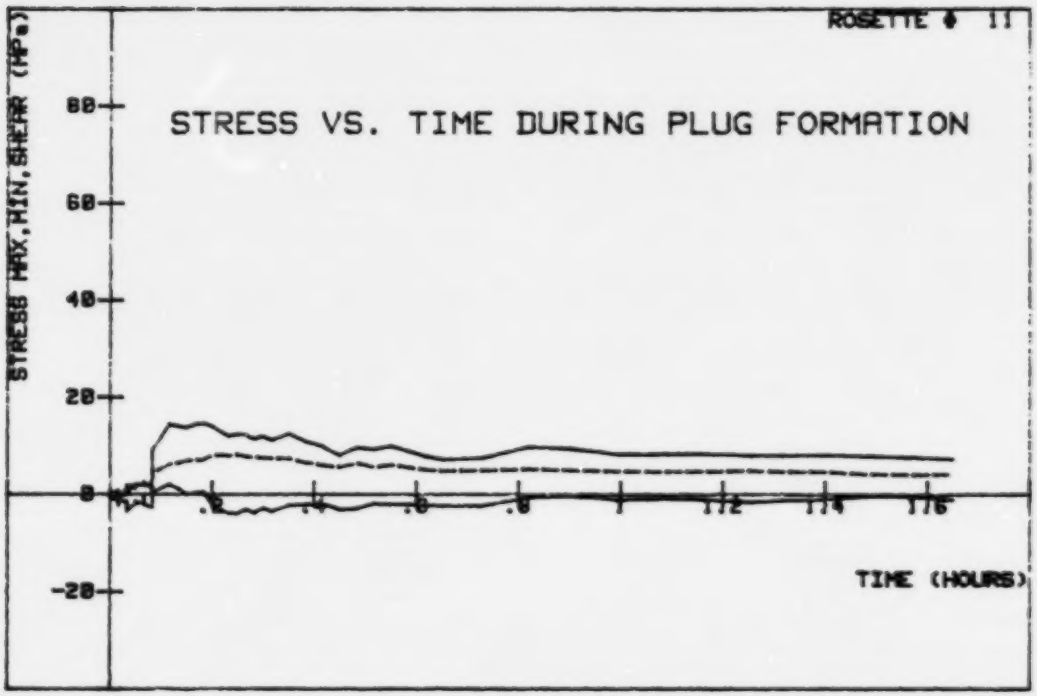

ROSETTE # 8
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX, MIN, SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

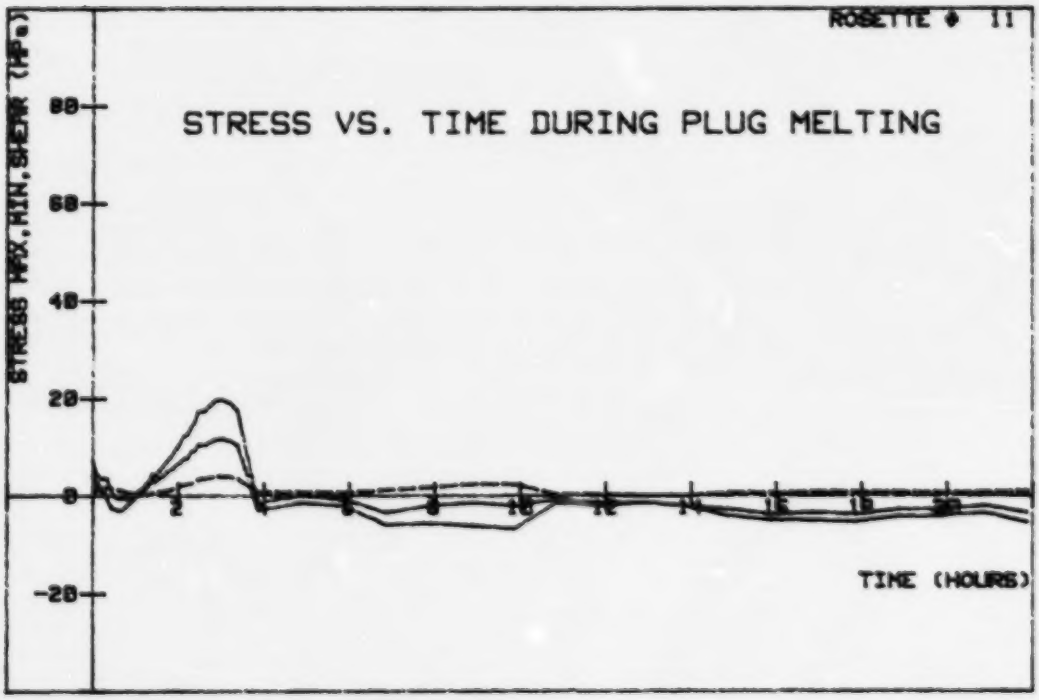

ROSETTE # 8
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/8
TIME (HOURS)

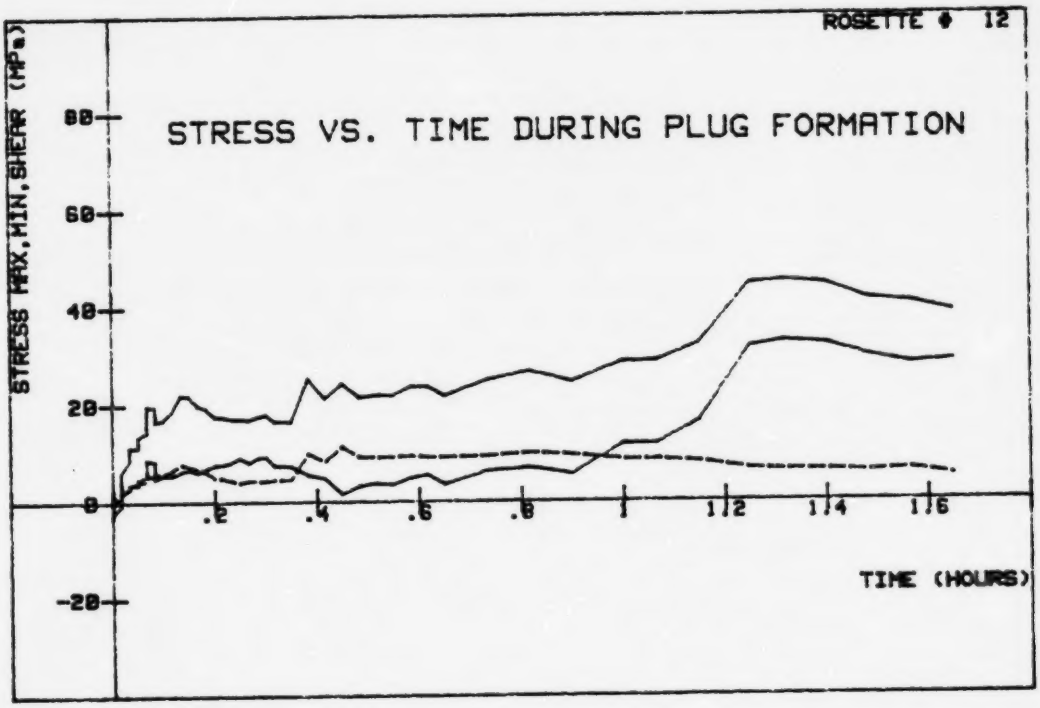

ROSETTE # 8
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX.,MIN.,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

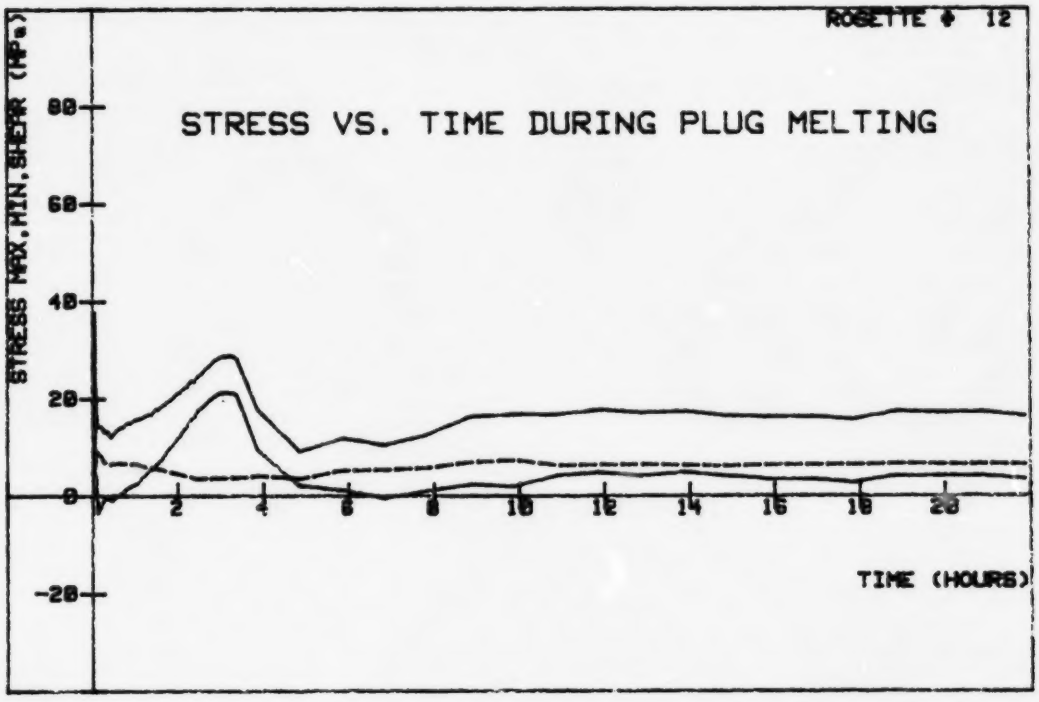

ROSETTE # 18
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1/2
1/4
1/6
TIME (HOURS)

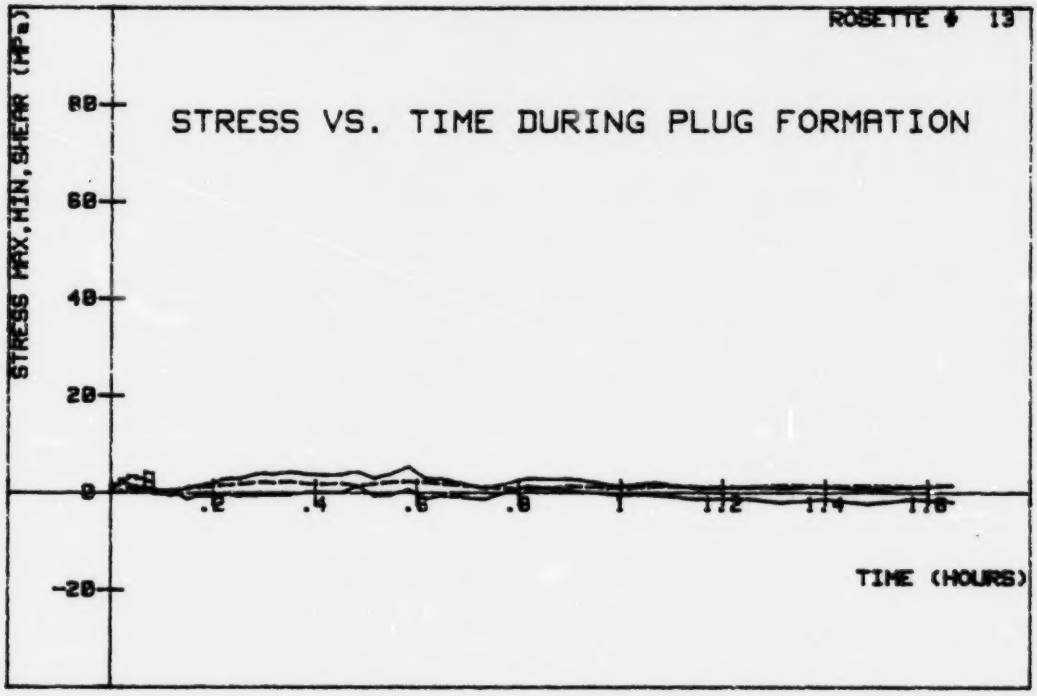

ROSETTE # 18
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

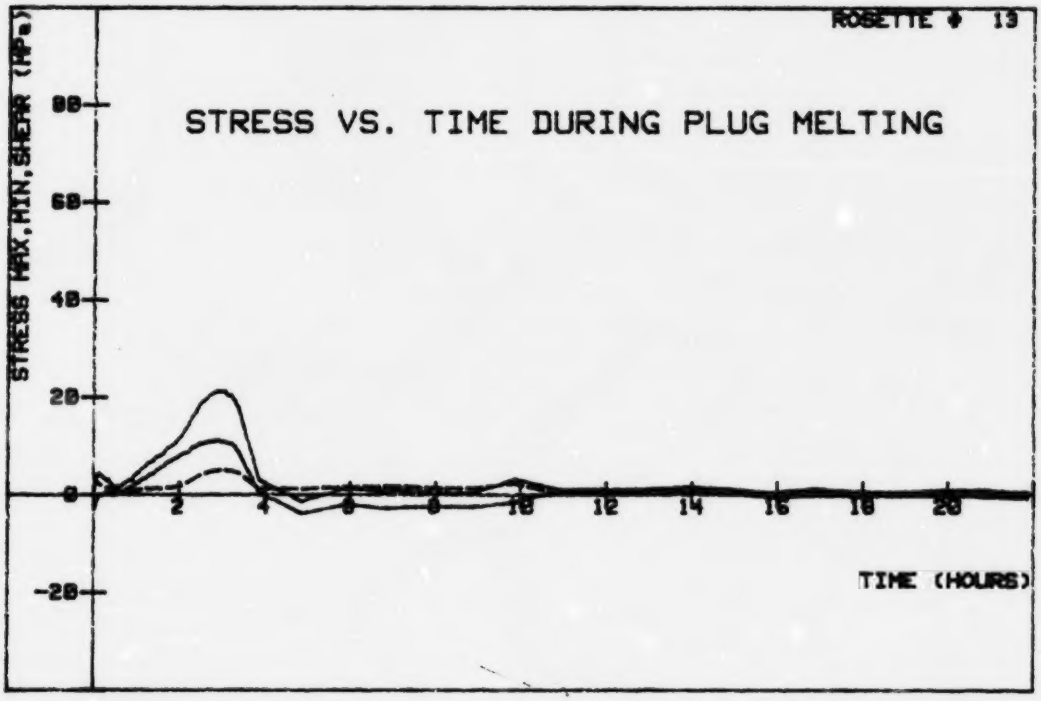

ROSETTE # 11
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

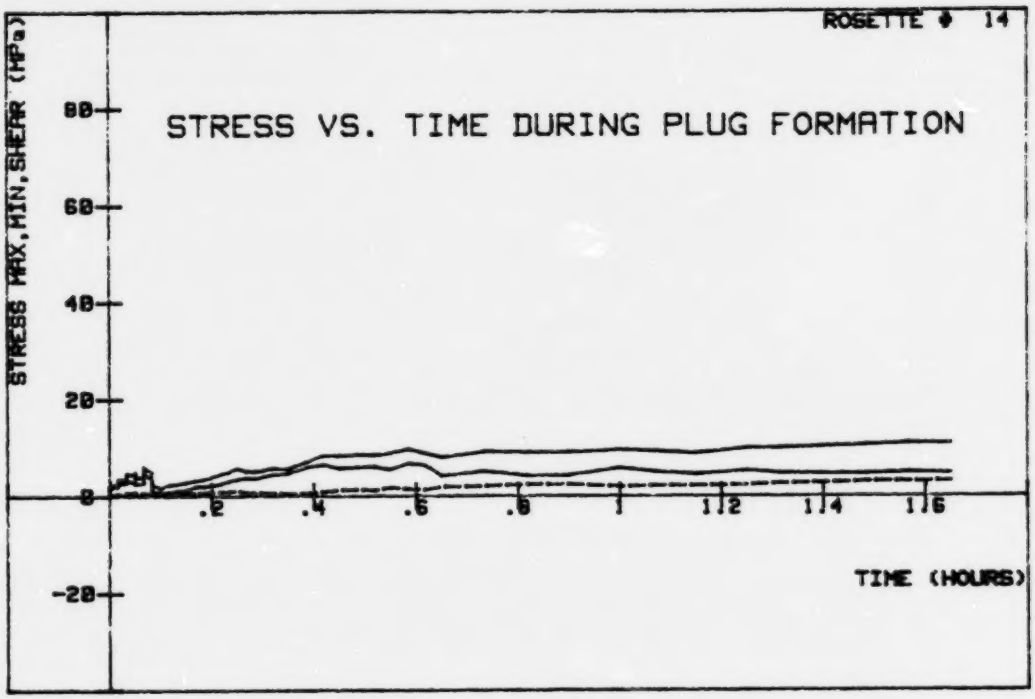

ROSETTE # 11
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
TIME (HOURS)

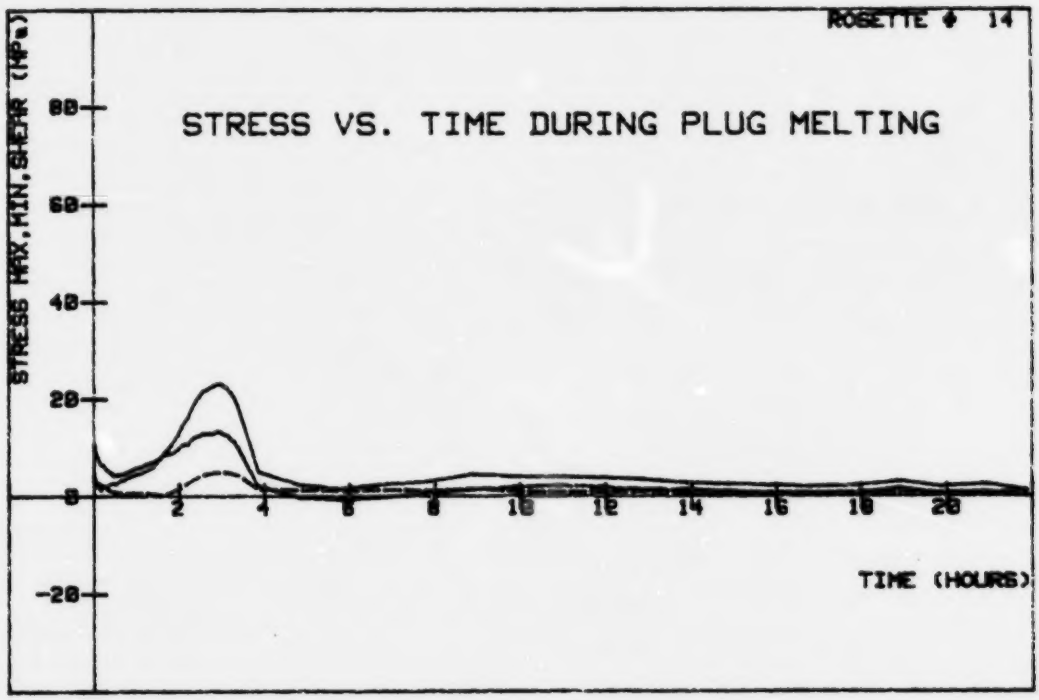

ROSETTE # 12
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

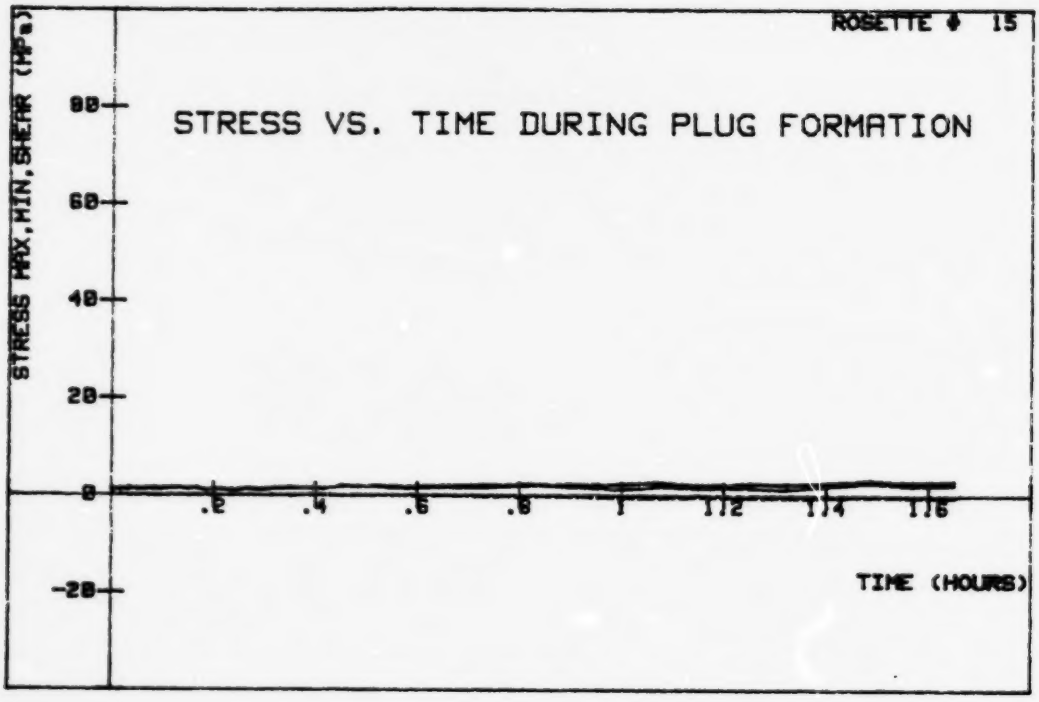

ROSETTE # 12
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

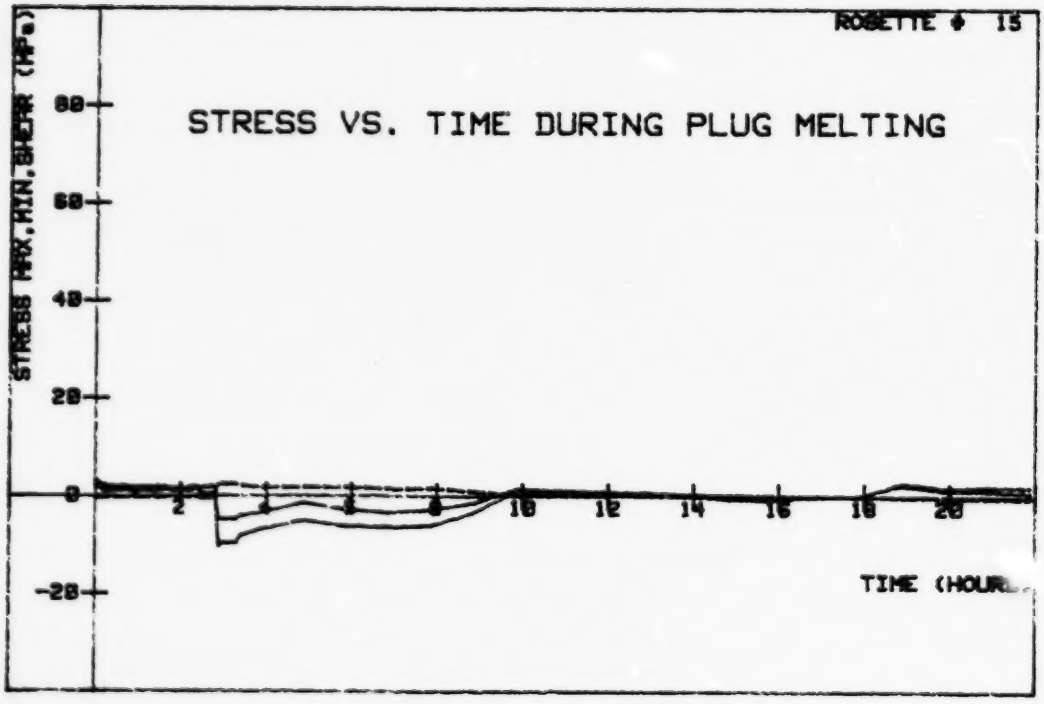

ROSETTE # 13
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)


ROSETTE # 13
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

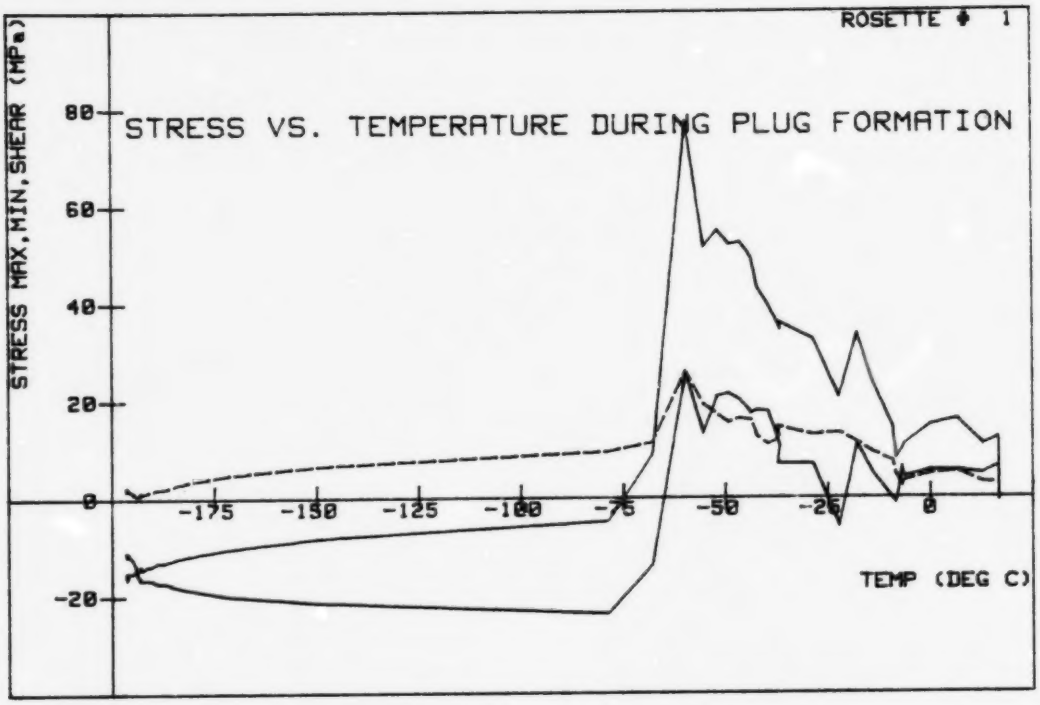

ROSETTE # 14
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX.MIN.SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

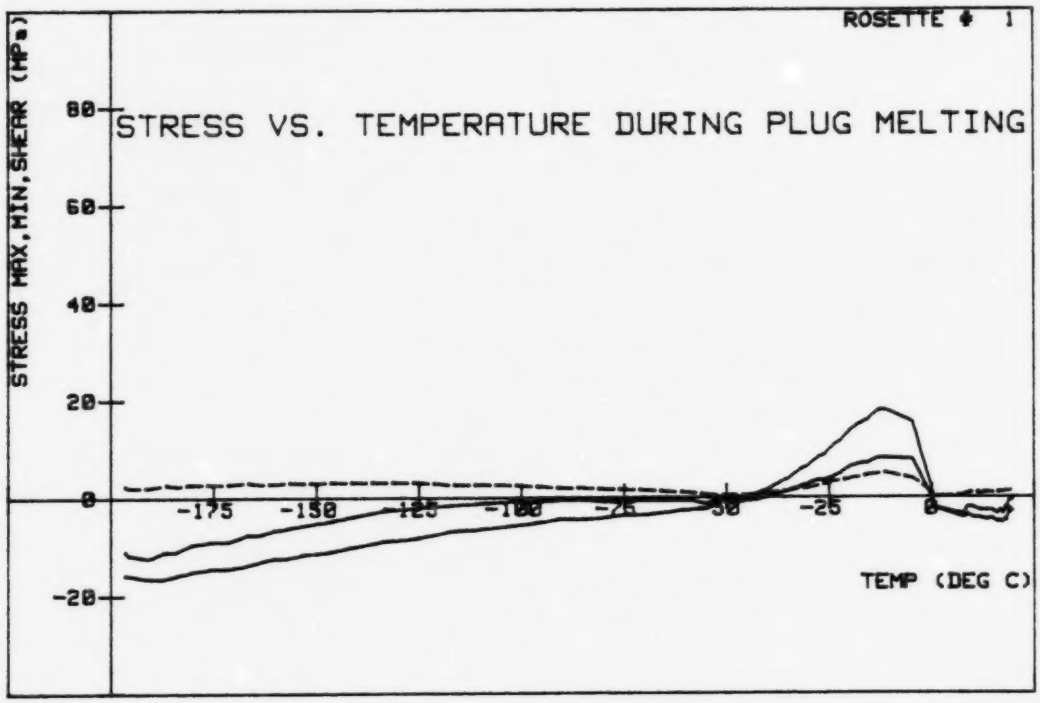

ROSETTE # 14
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX.MIN.SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

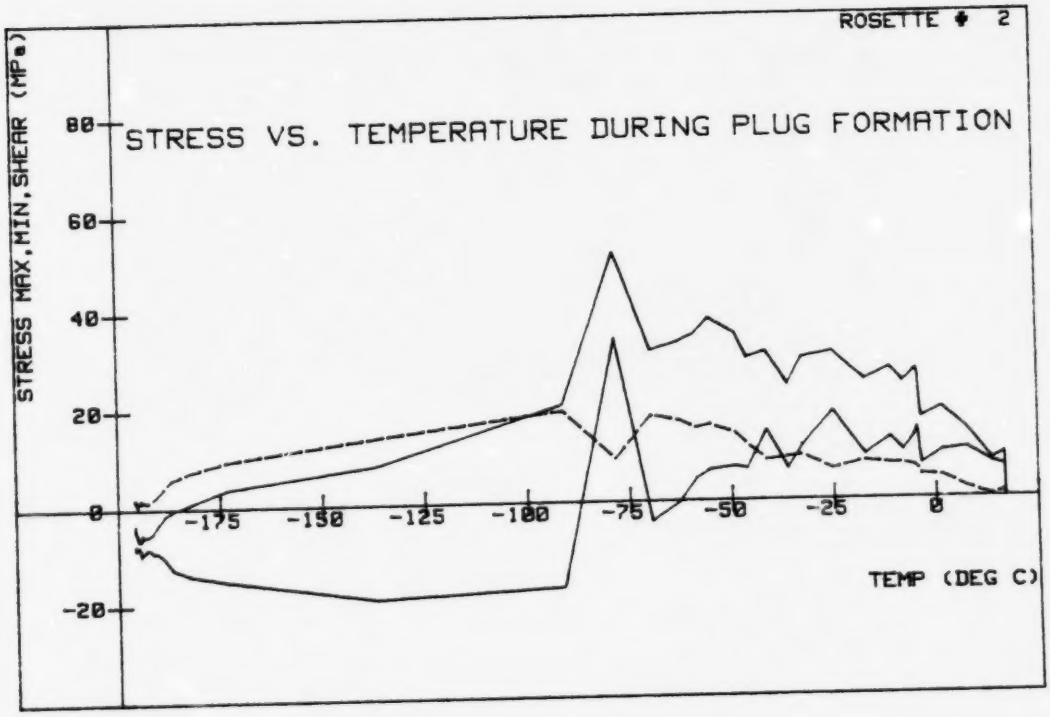

ROSETTE # 15
STRESS VS. TIME DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

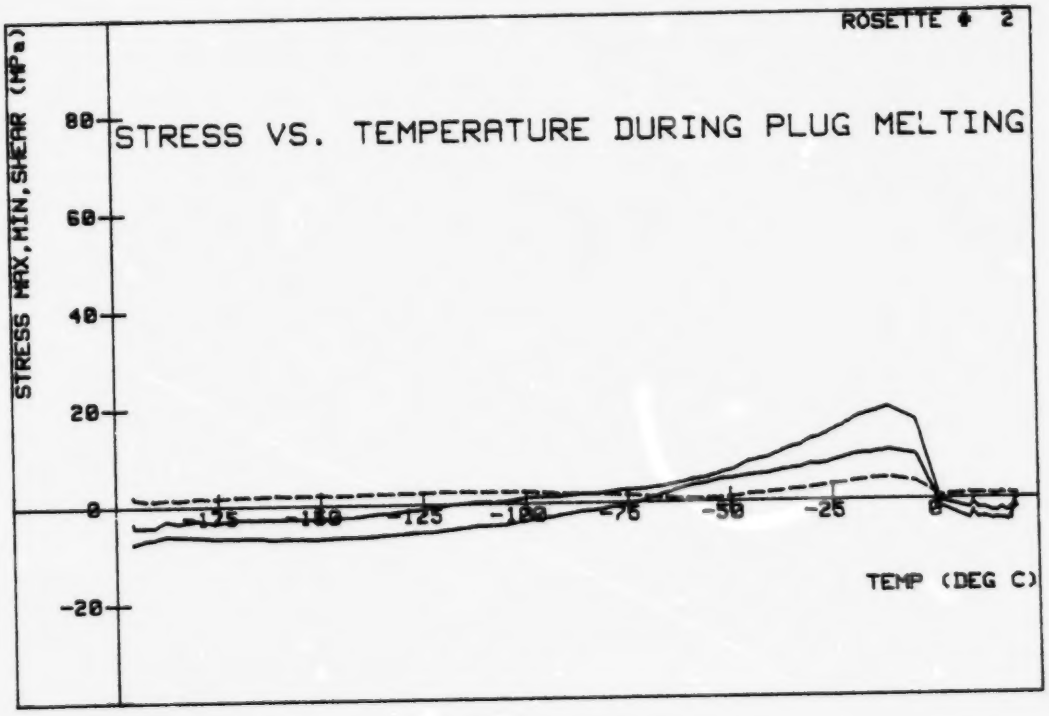

ROSETTE # 15
STRESS VS. TIME DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
2
4
6
8
10
12
14
16
18
20
TIME (HOUR

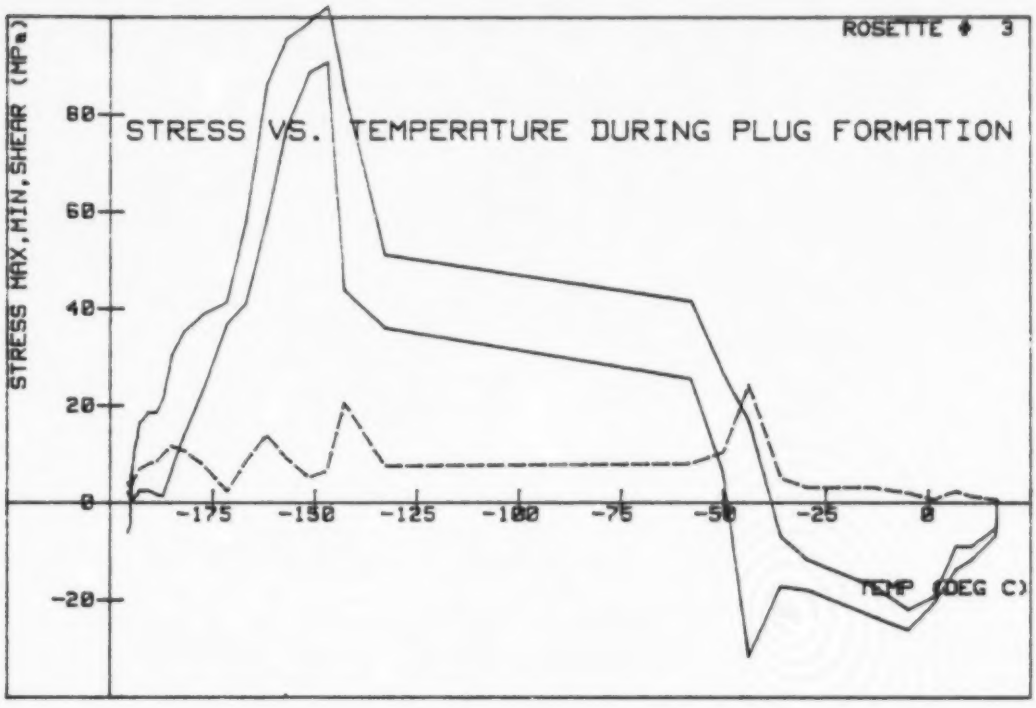
STRESS VS TEMPERATURE

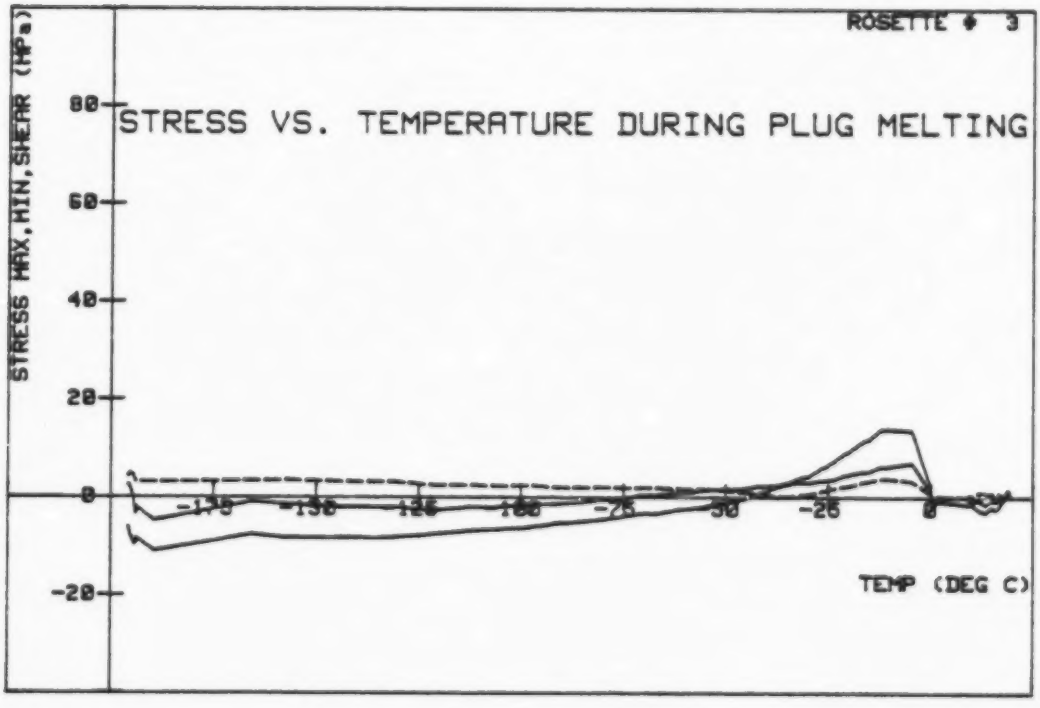

ROSETTE # 1
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

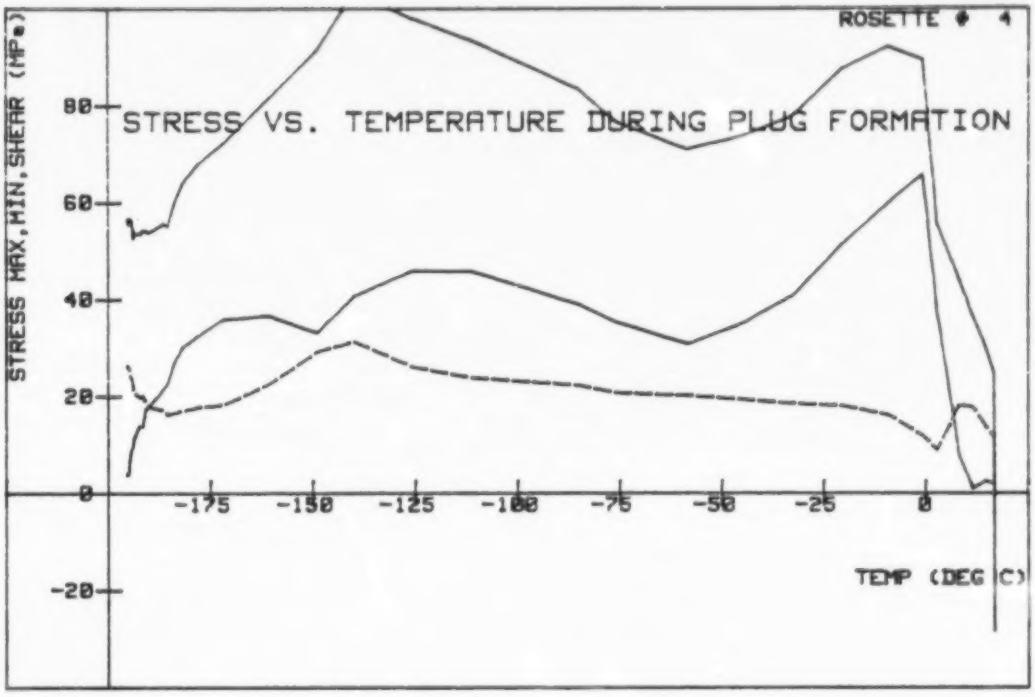

ROSETTE # 1
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-25
50
-25
0
TEMP (DEG C)

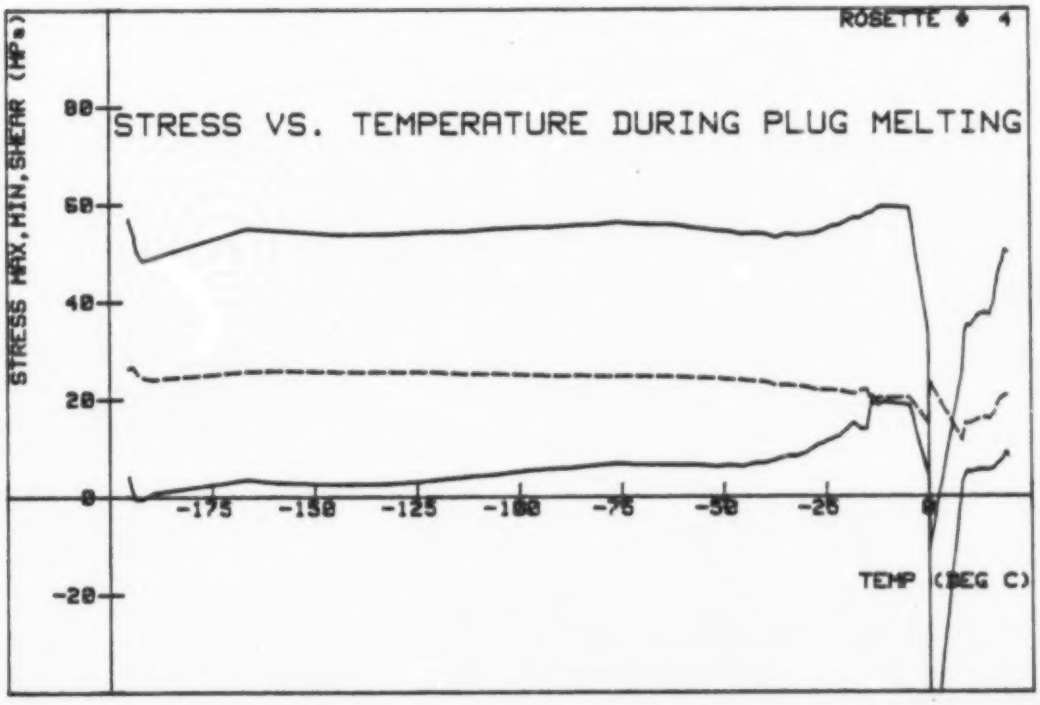

ROSETTE # 2
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

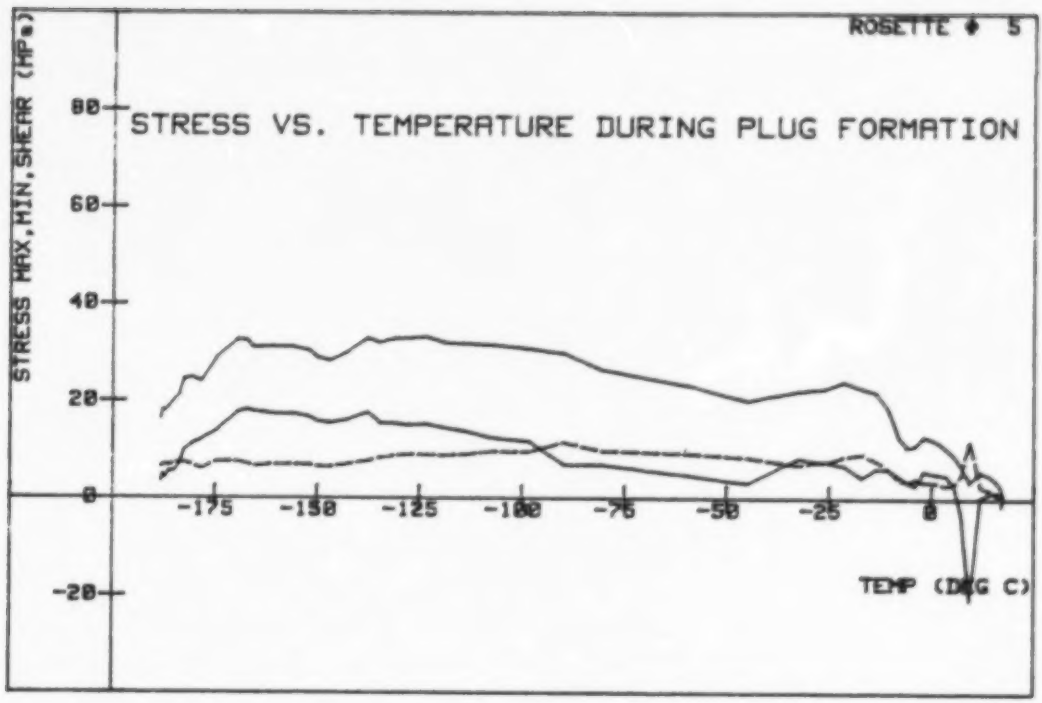

ROSETTE # 2
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

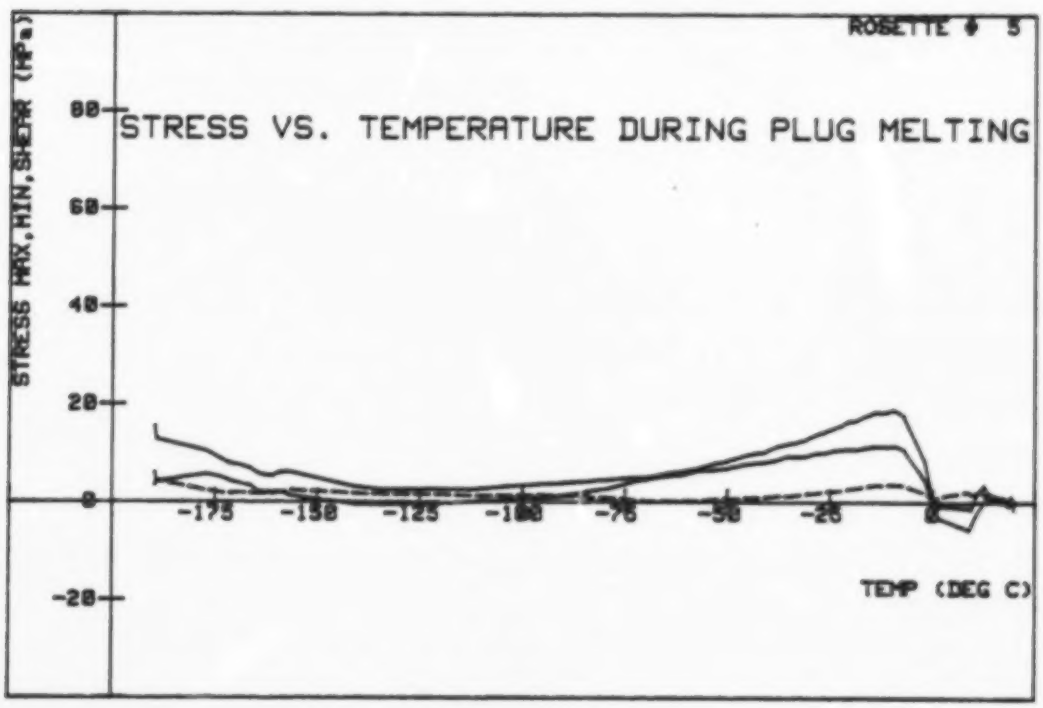

ROSETTE # 3
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

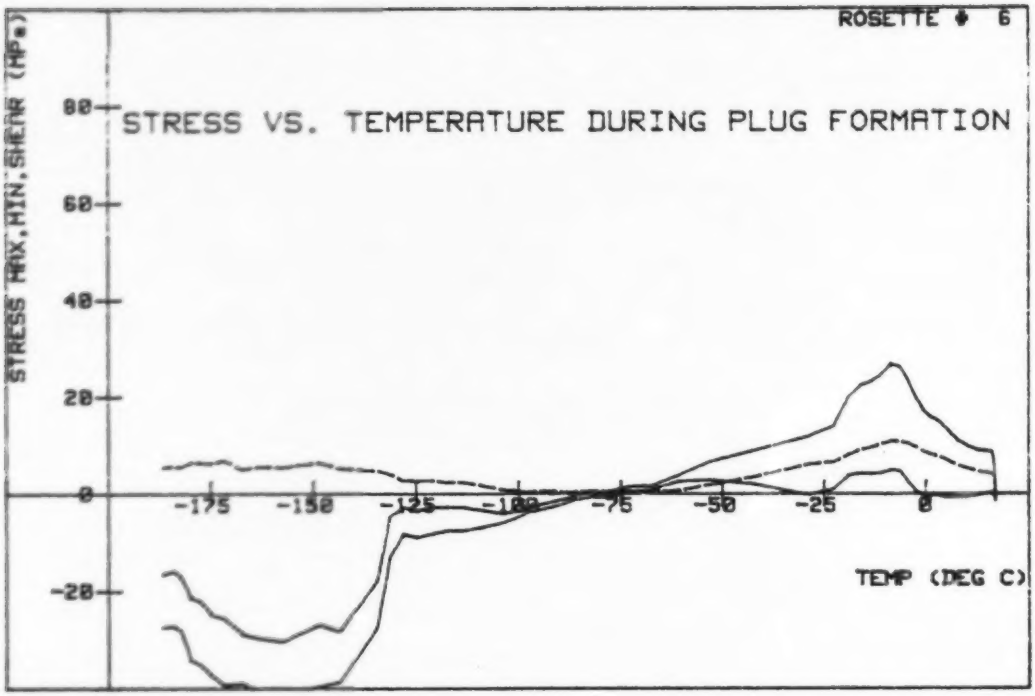

ROSETTE # 3
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
TEMP (DEG C)

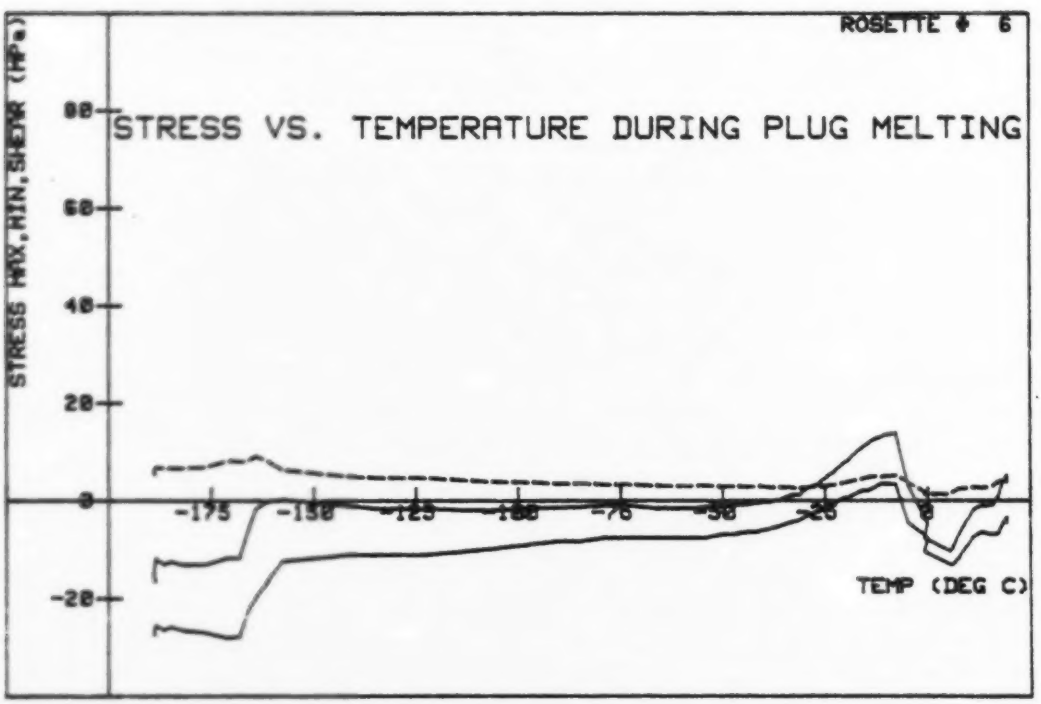

ROSETTE # 4
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

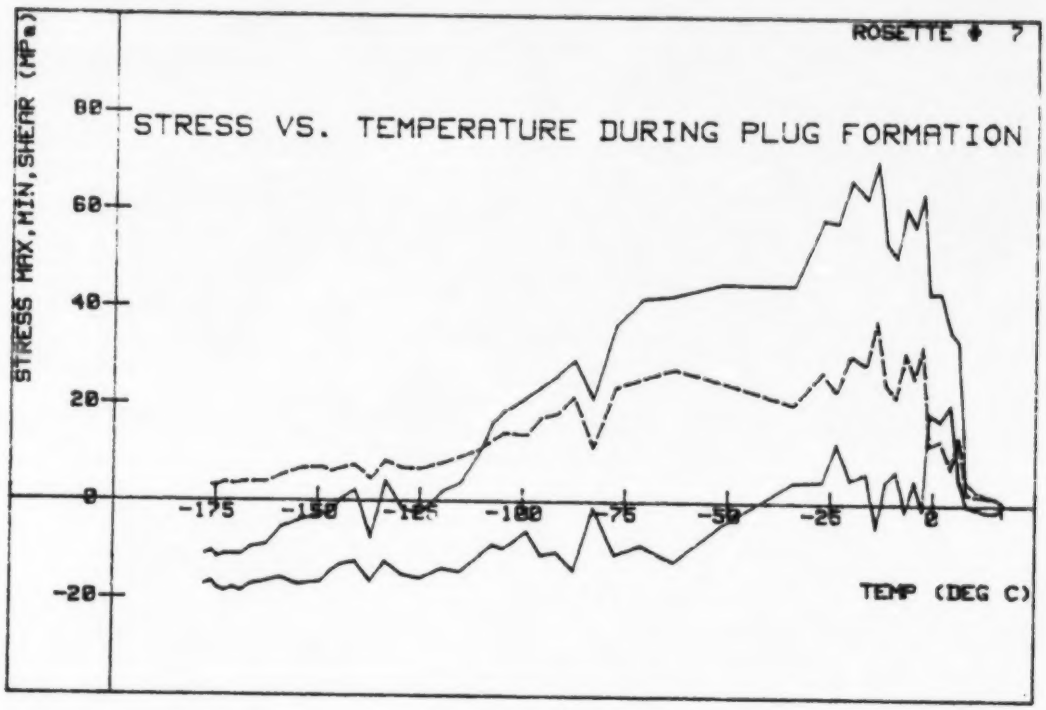

ROSETTE # 4
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

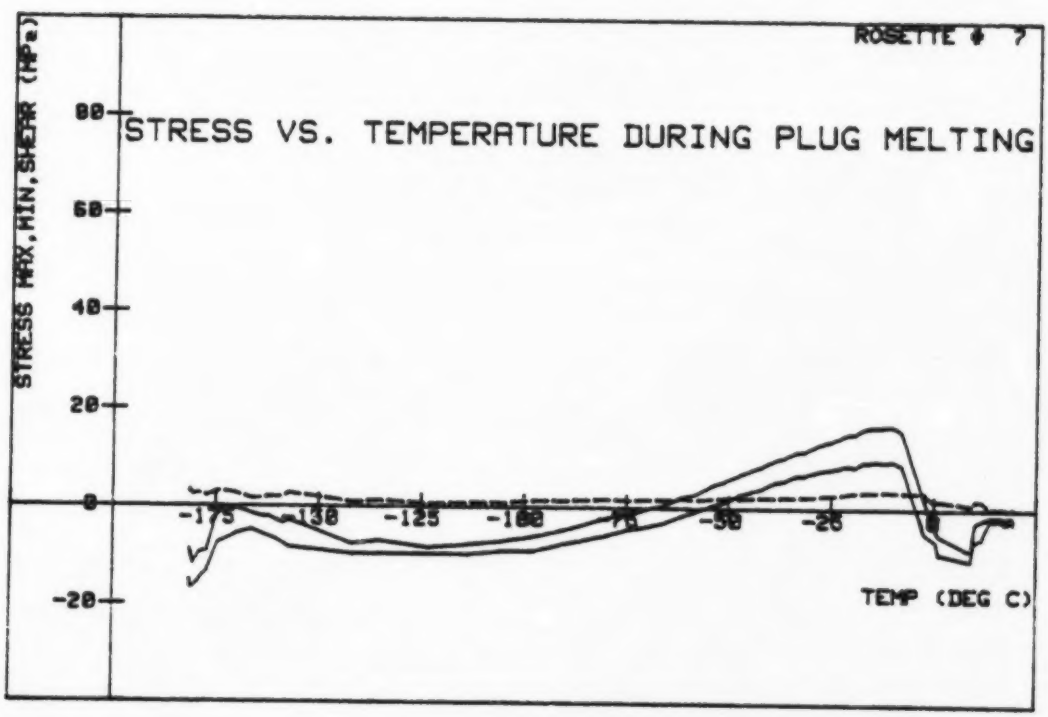

ROSETTE # 5
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

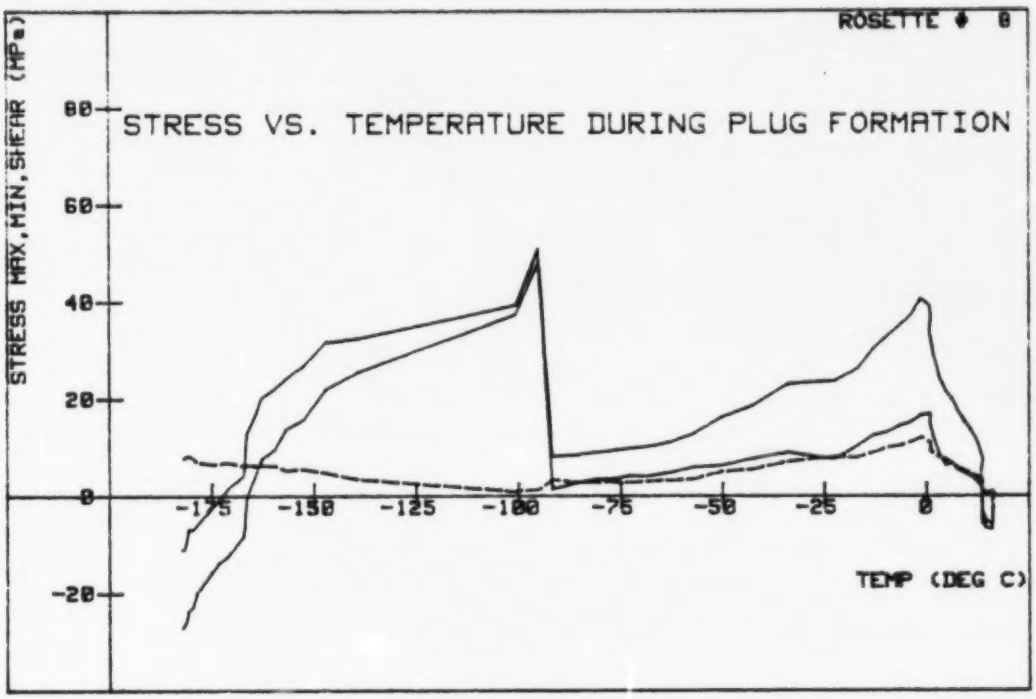

ROSETTE # 5
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

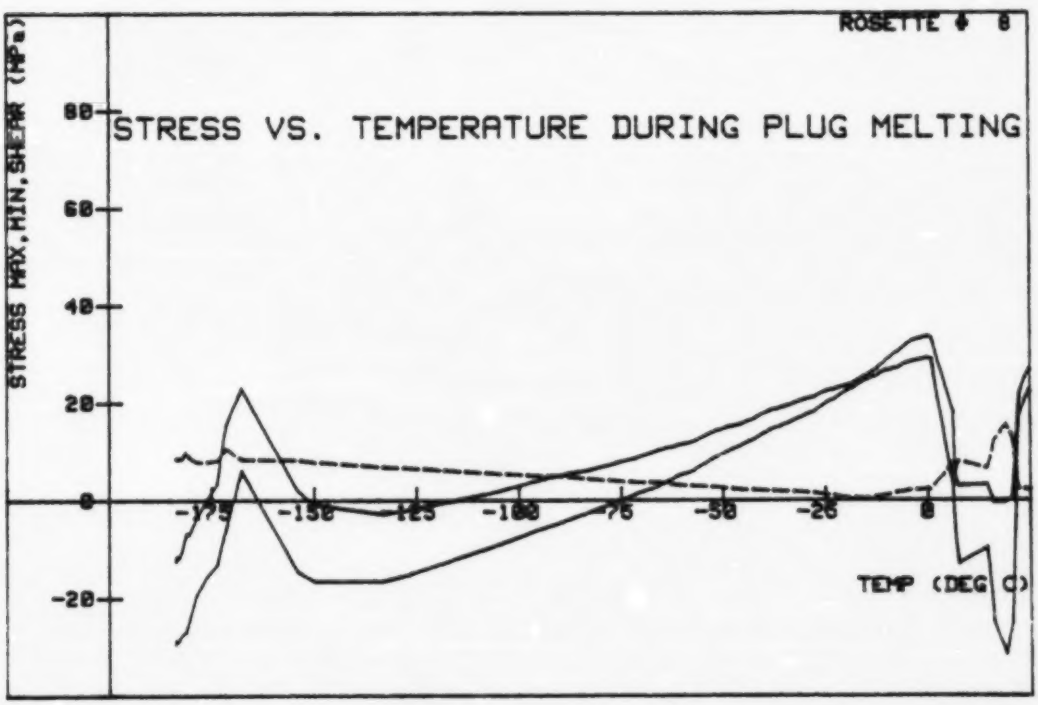

ROSETTE # 6
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

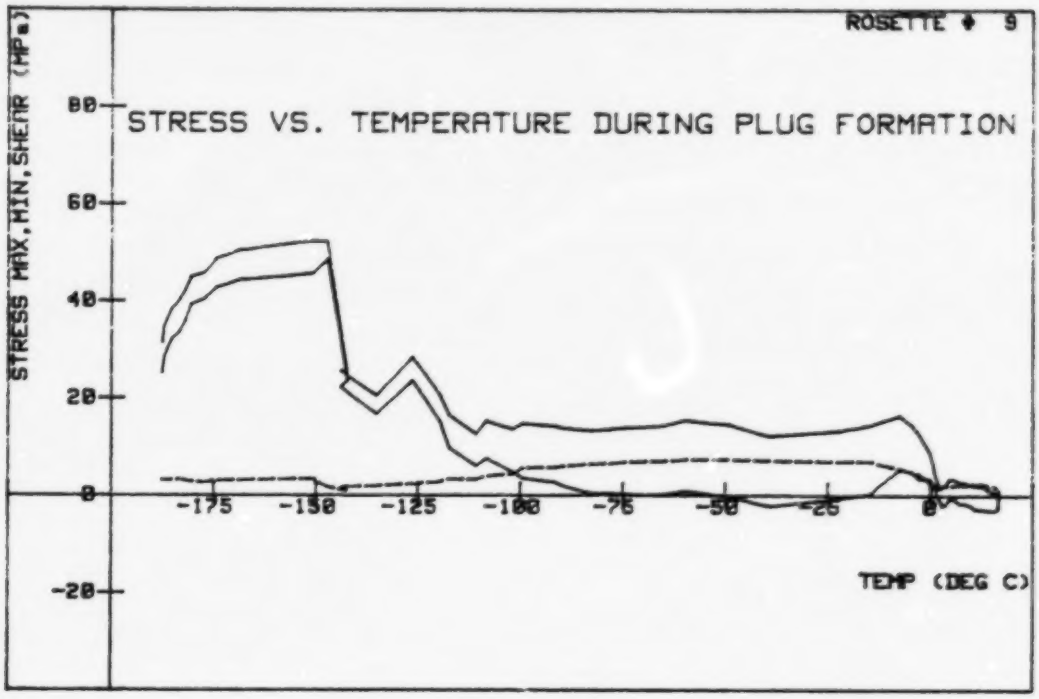

ROSETTE # 6
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

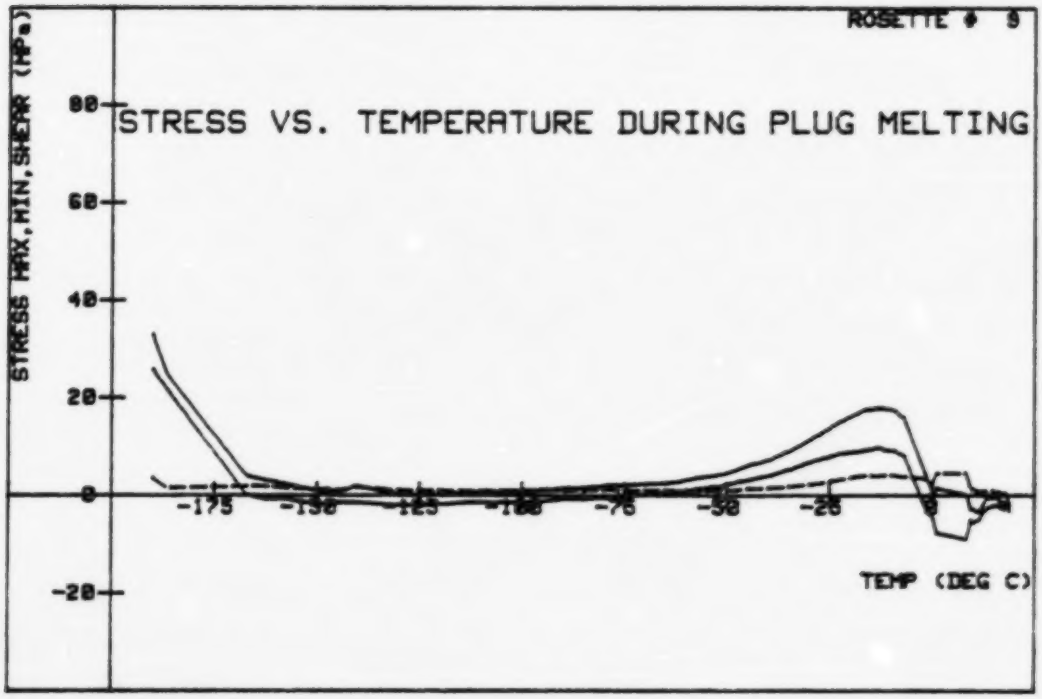

ROSETTE # 7
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

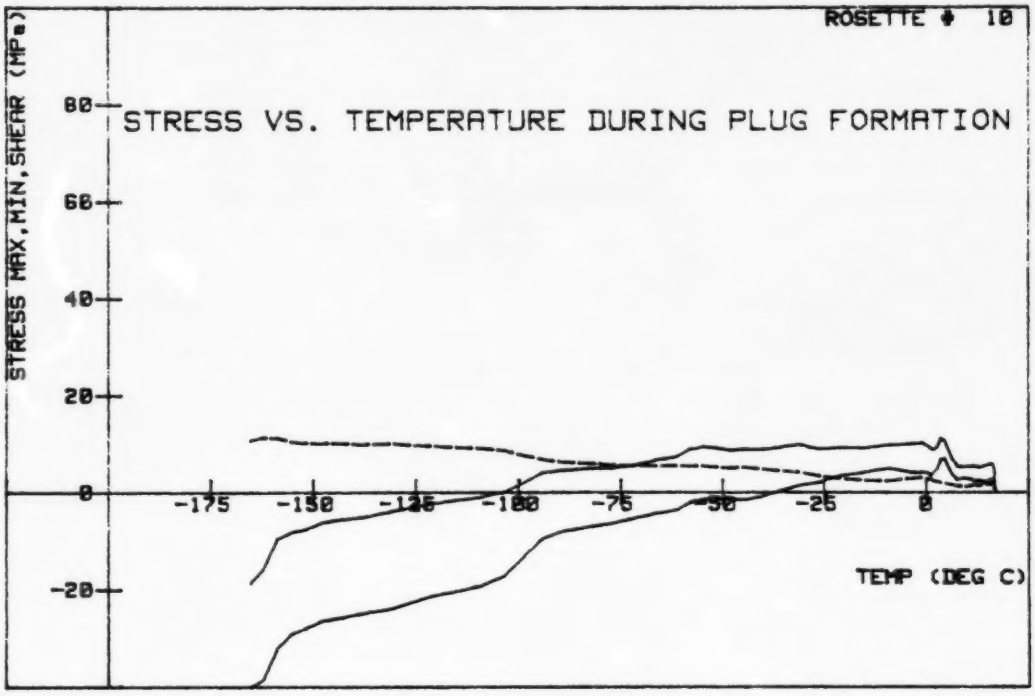

ROSETTE # 7
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

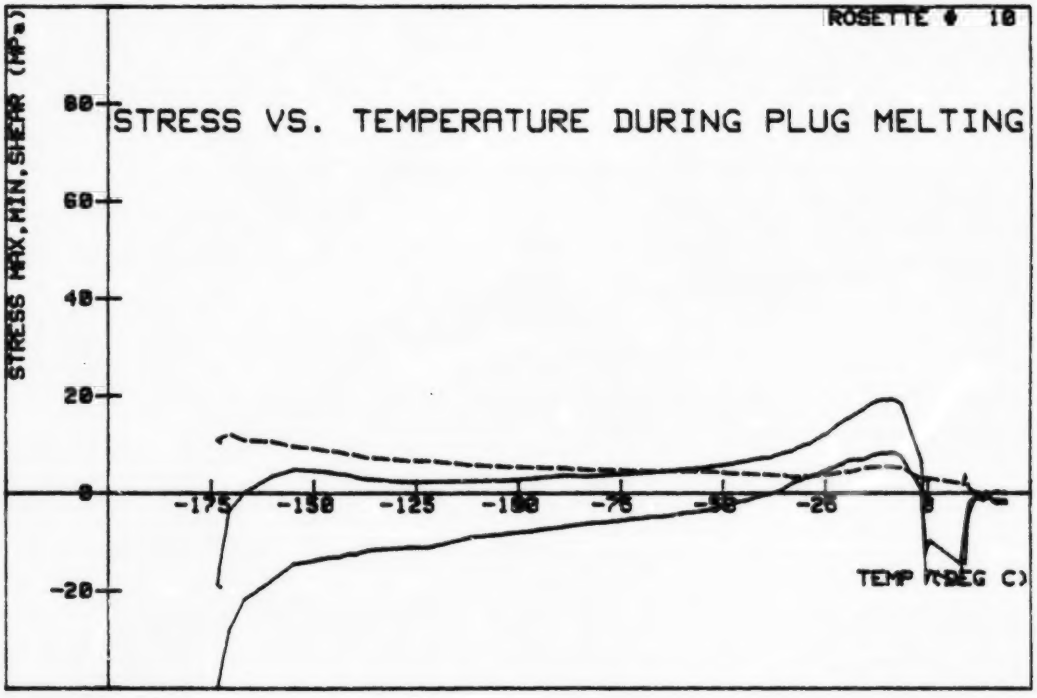

ROSETTE # 8
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

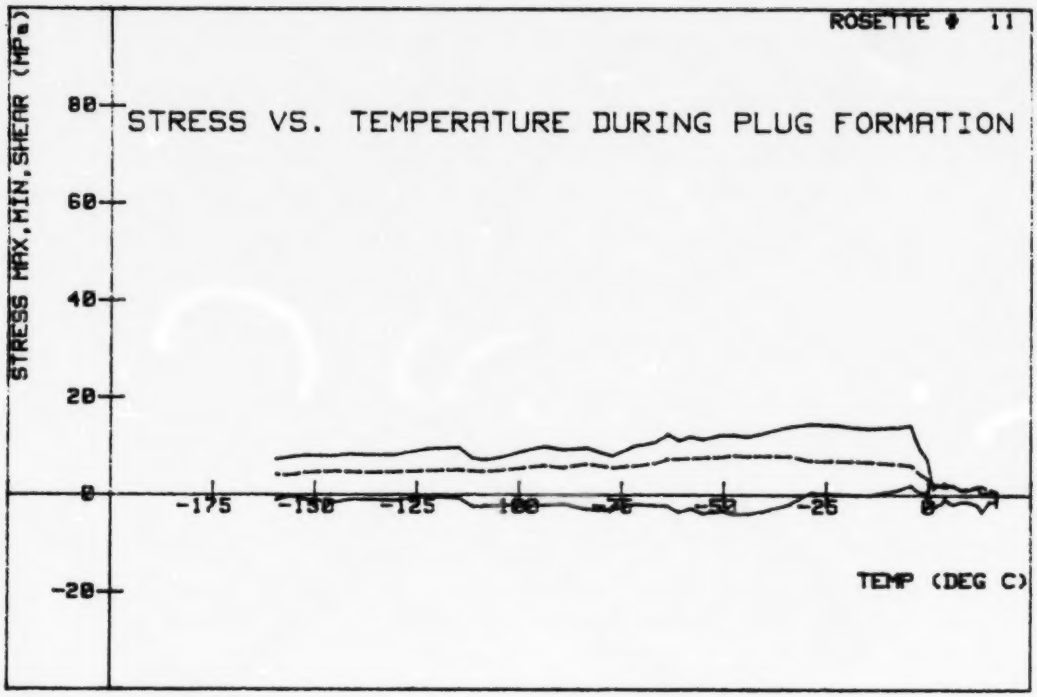

ROSETTE # 8
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

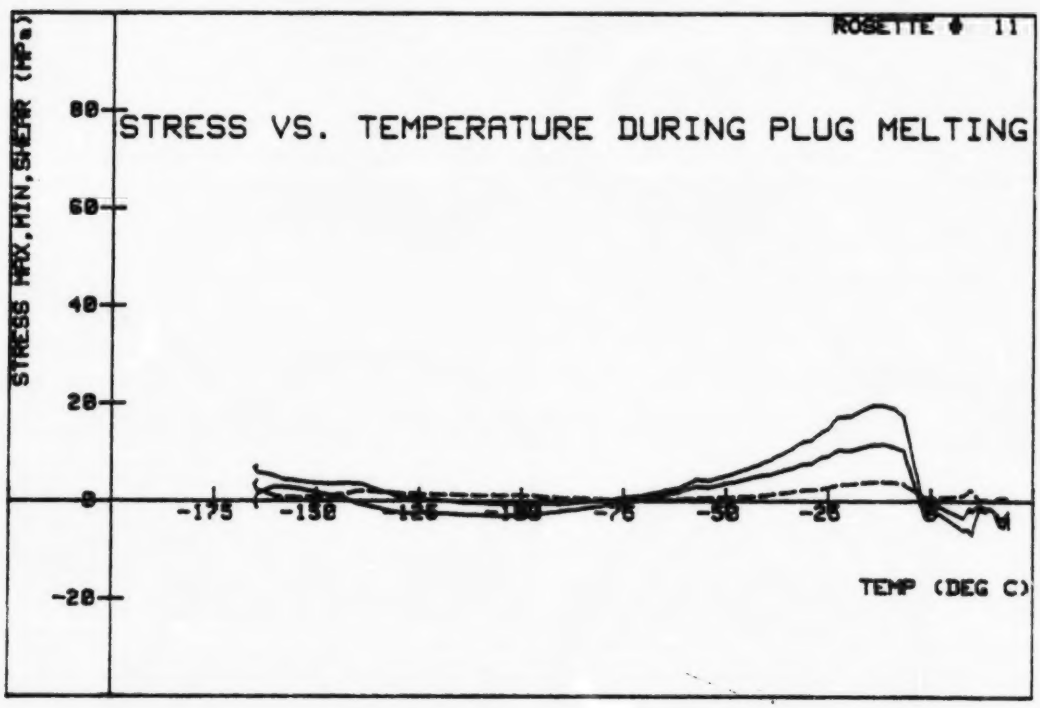

ROSETTE # 9
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

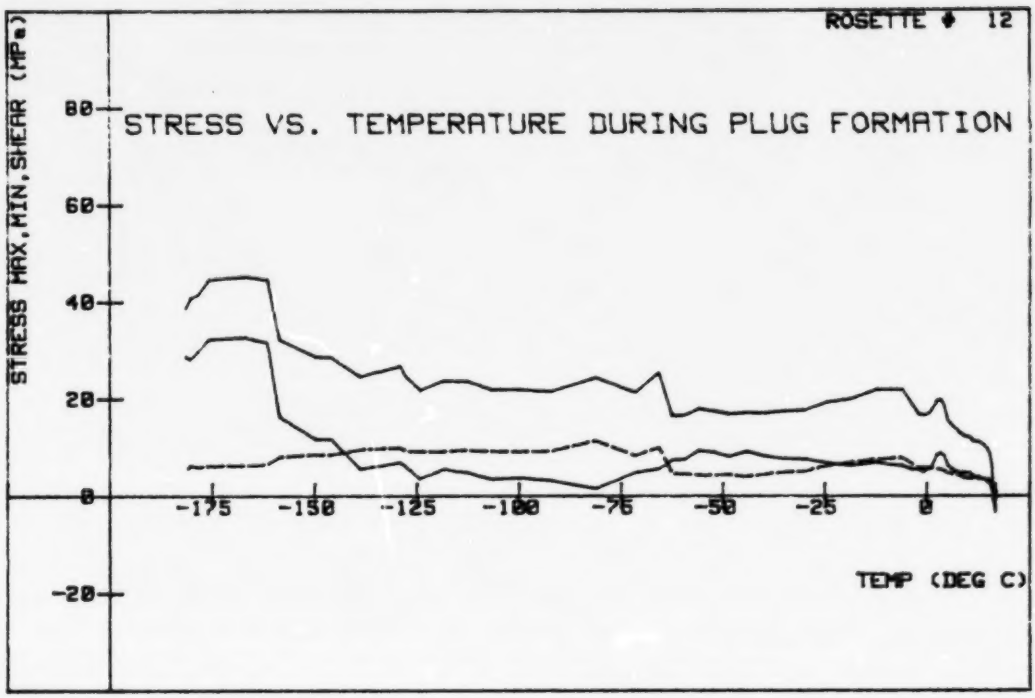

ROSETTE # 9
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

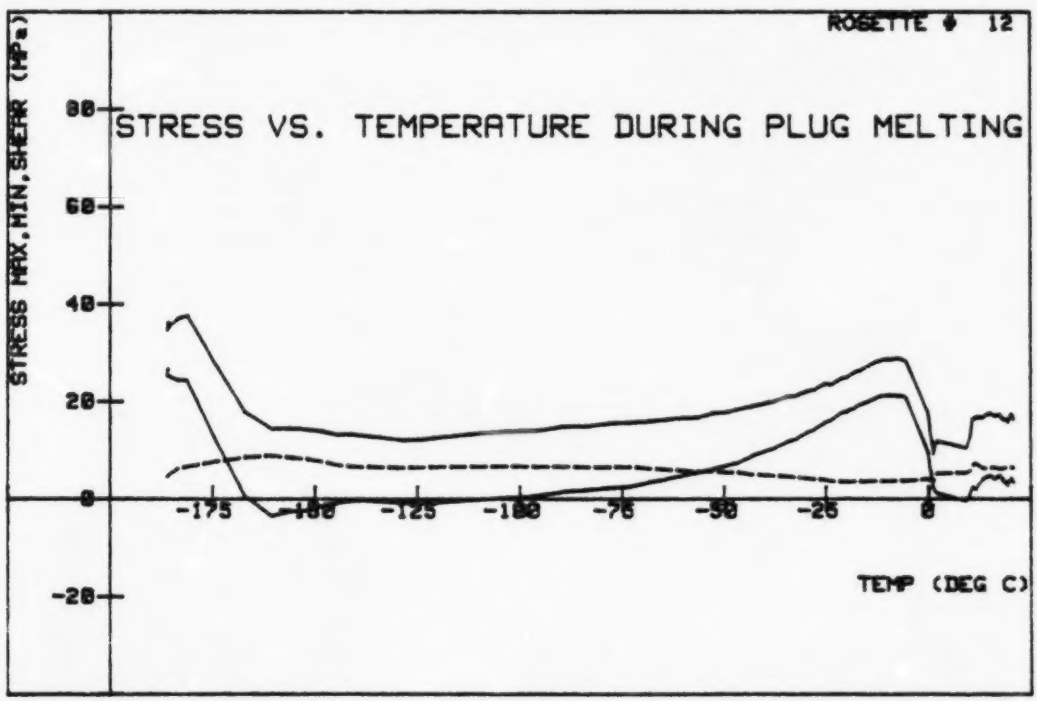

ROSETTE # 10
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

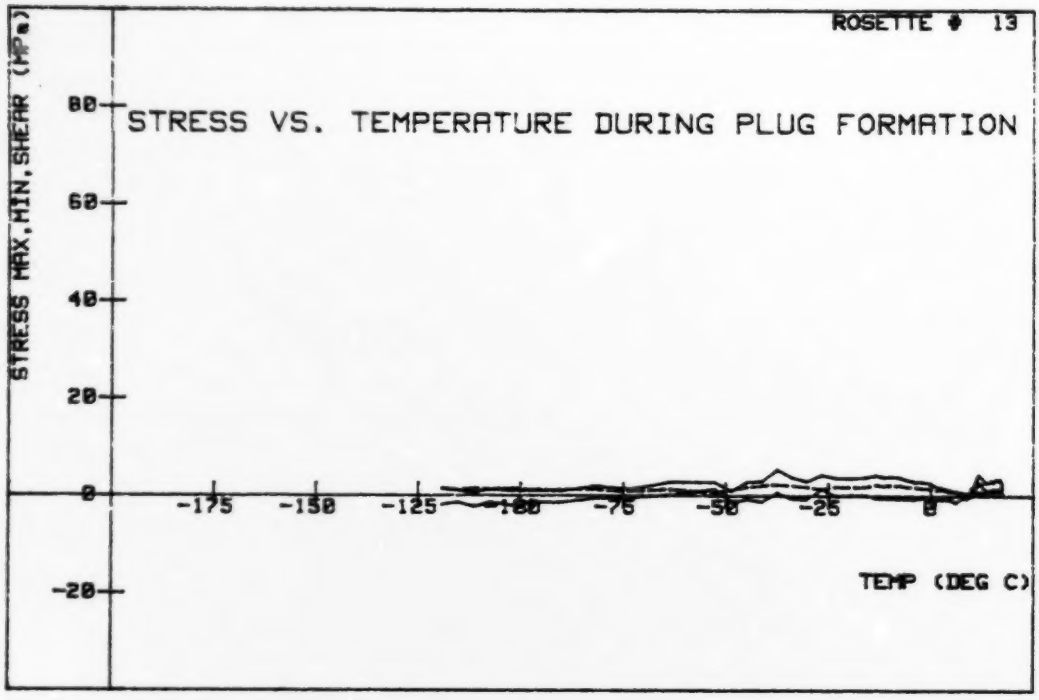

ROSETTE # 10
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

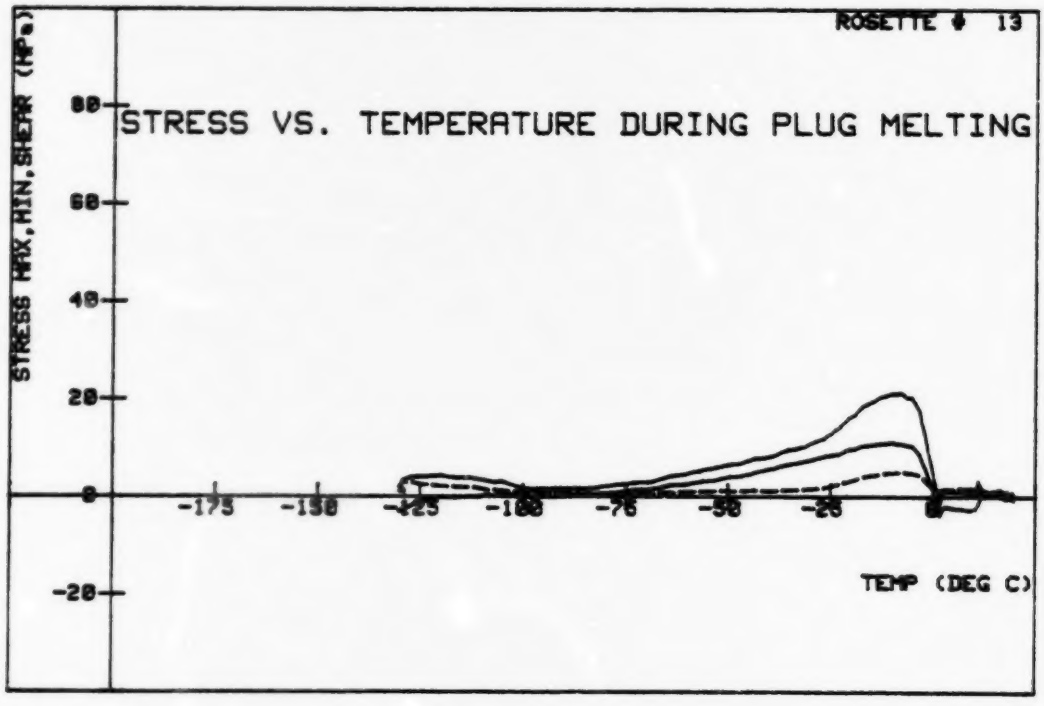

ROSETTE # 11
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

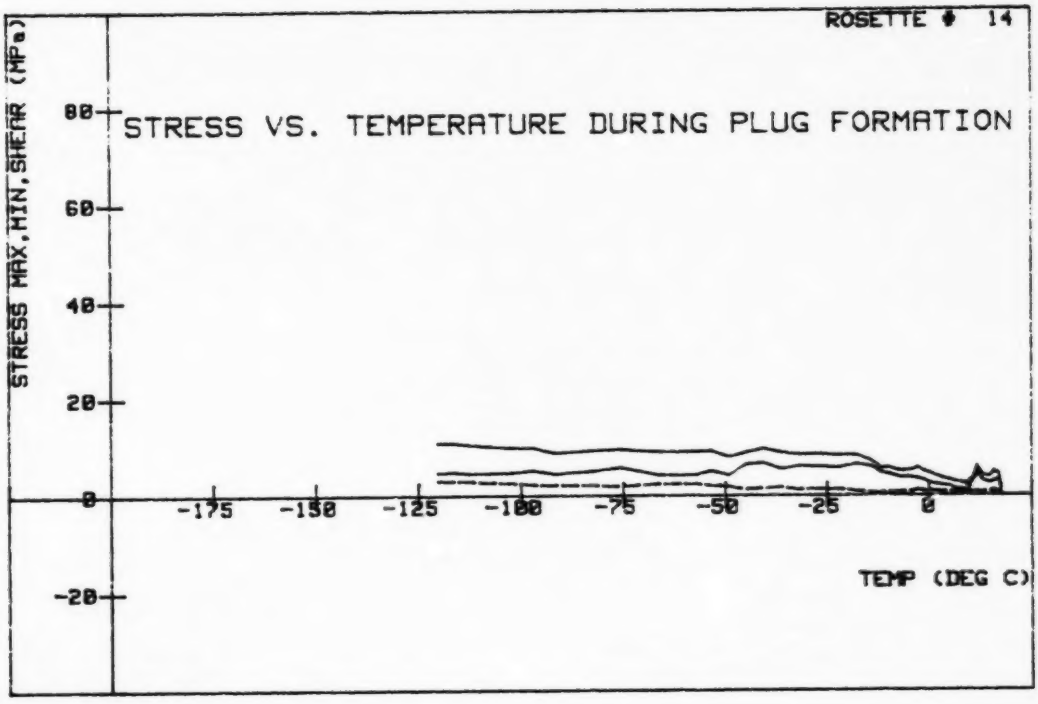

ROSETTE # 11
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-75
-50
-25
TEMP (DEG C)

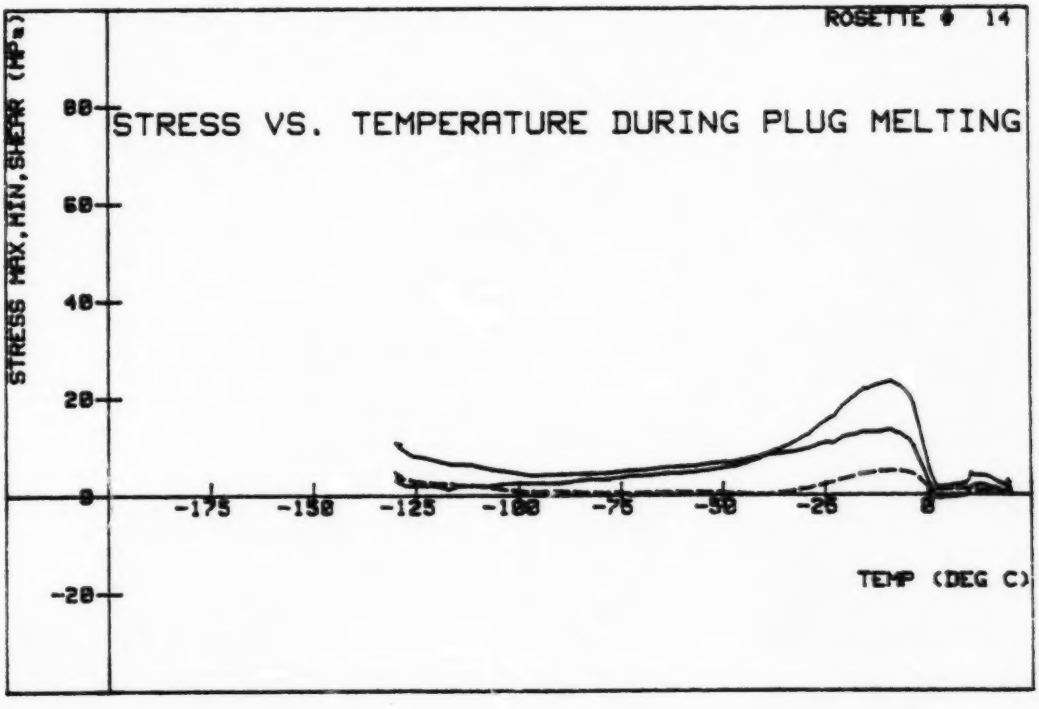

ROSETTE # 12
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

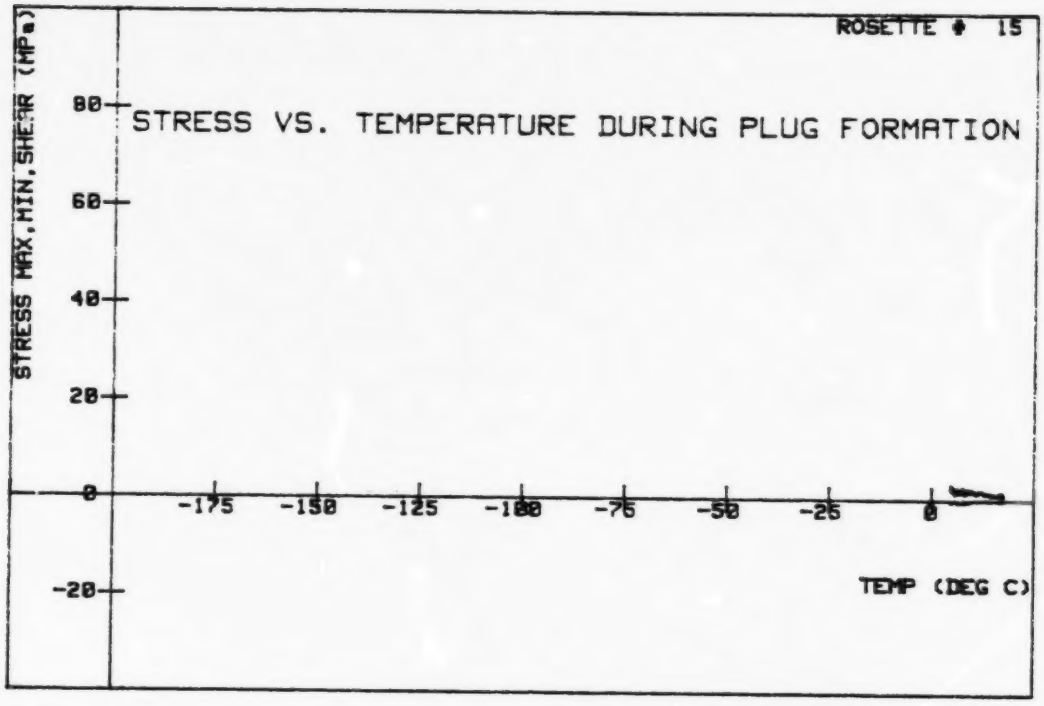

ROSETTE # 12
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-125
-75
-50
-25
0
TEMP (DEG C)

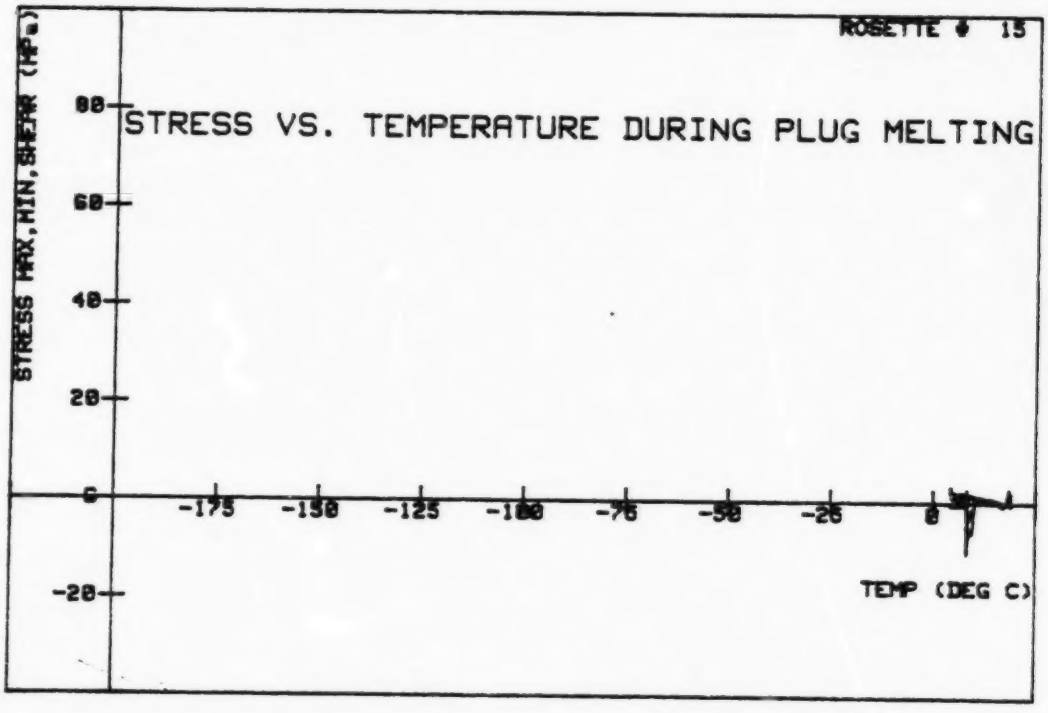

ROSETTE # 13
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)


ROSETTE # 13
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

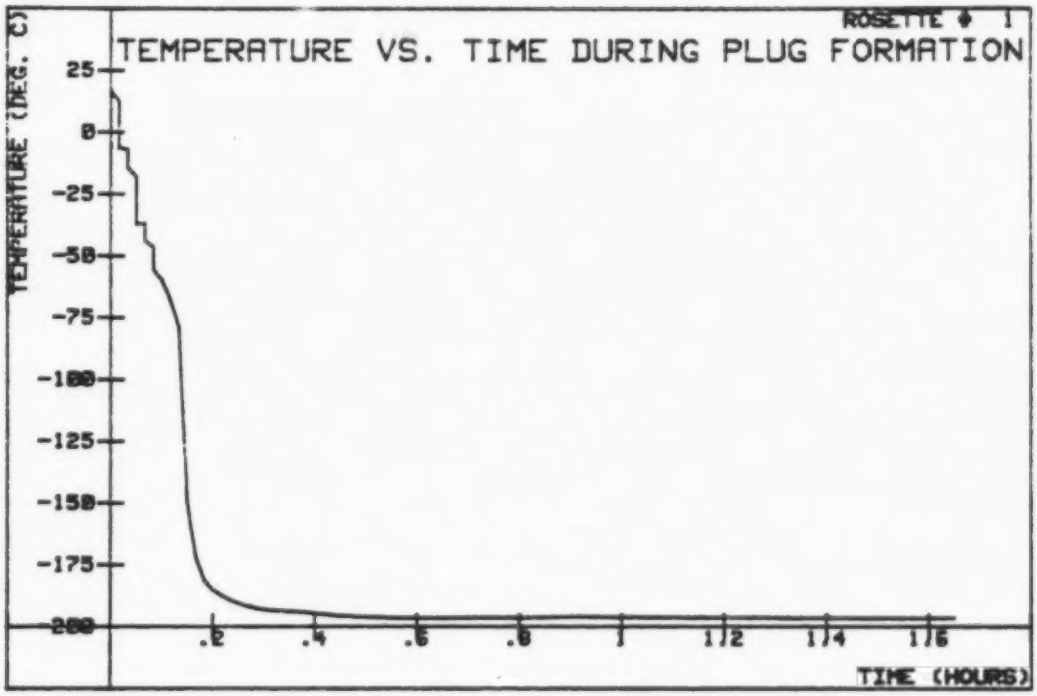

ROSETTE # 14
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

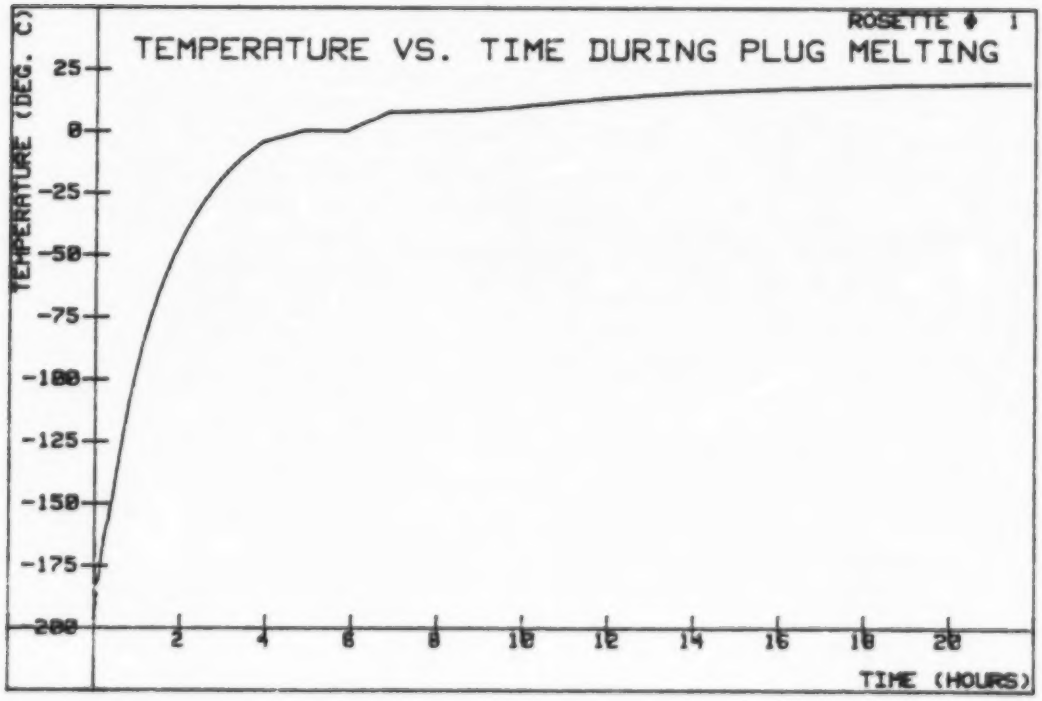

ROSETTE # 14
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

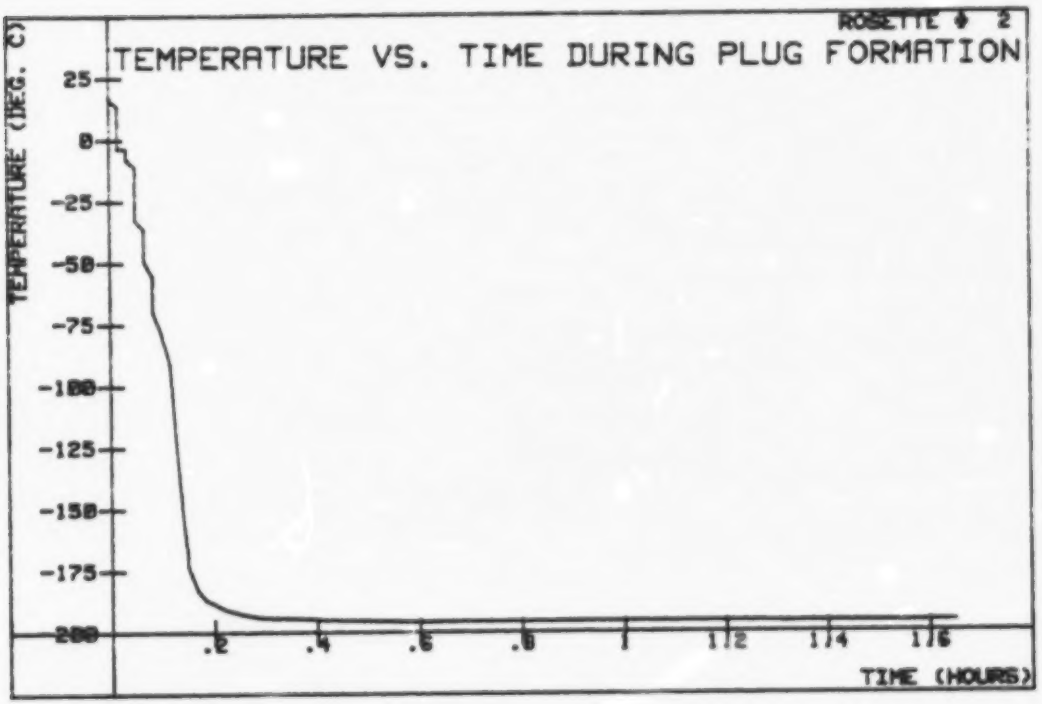

ROSETTE # 15
STRESS VS. TEMPERATURE DURING PLUG FORMATION
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

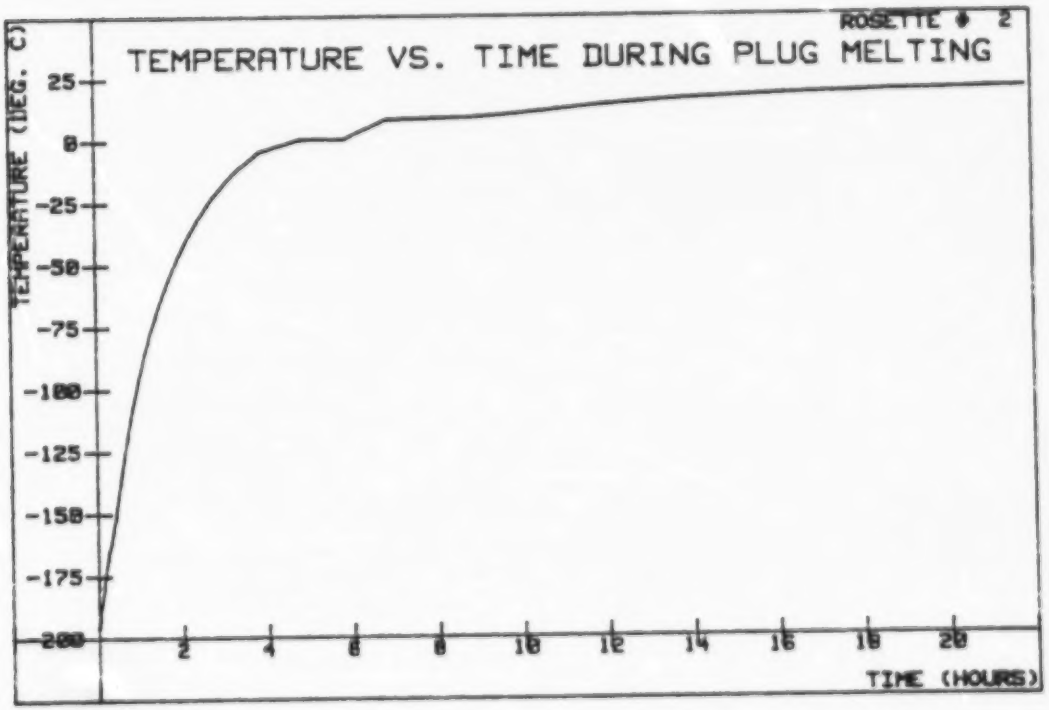

ROSETTE # 15
STRESS VS. TEMPERATURE DURING PLUG MELTING
STRESS MAX,MIN,SHEAR (MPa)
80
60
40
20
0
-20
-175
-150
-125
-100
-75
-50
-25
0
TEMP (DEG C)

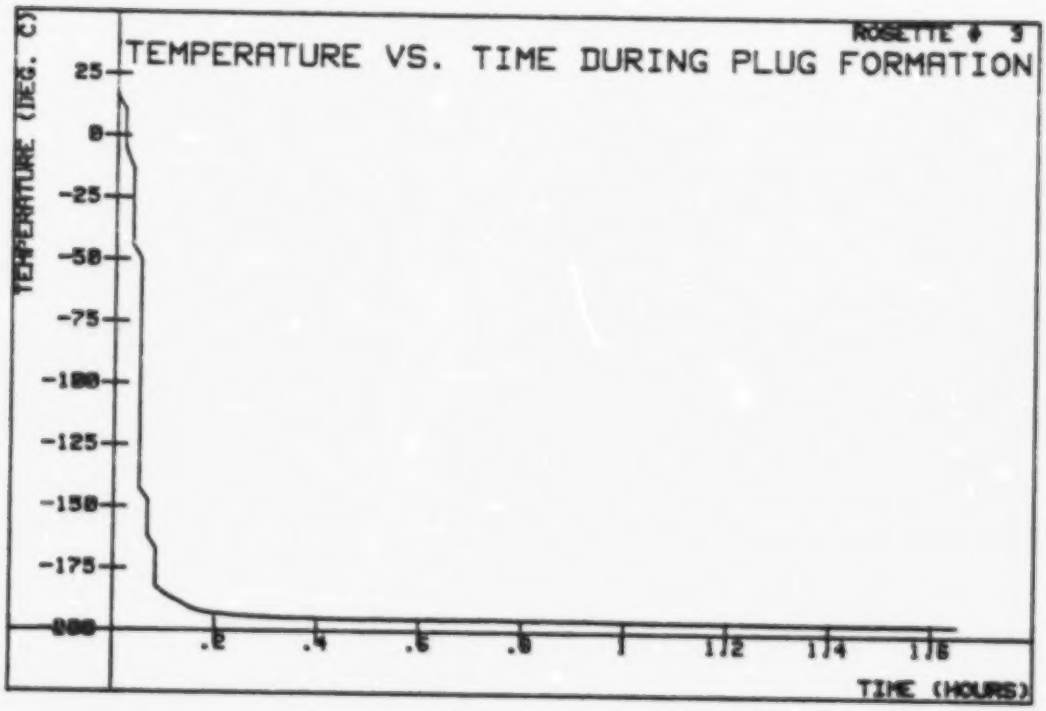
TEMPERATURE VS TIME

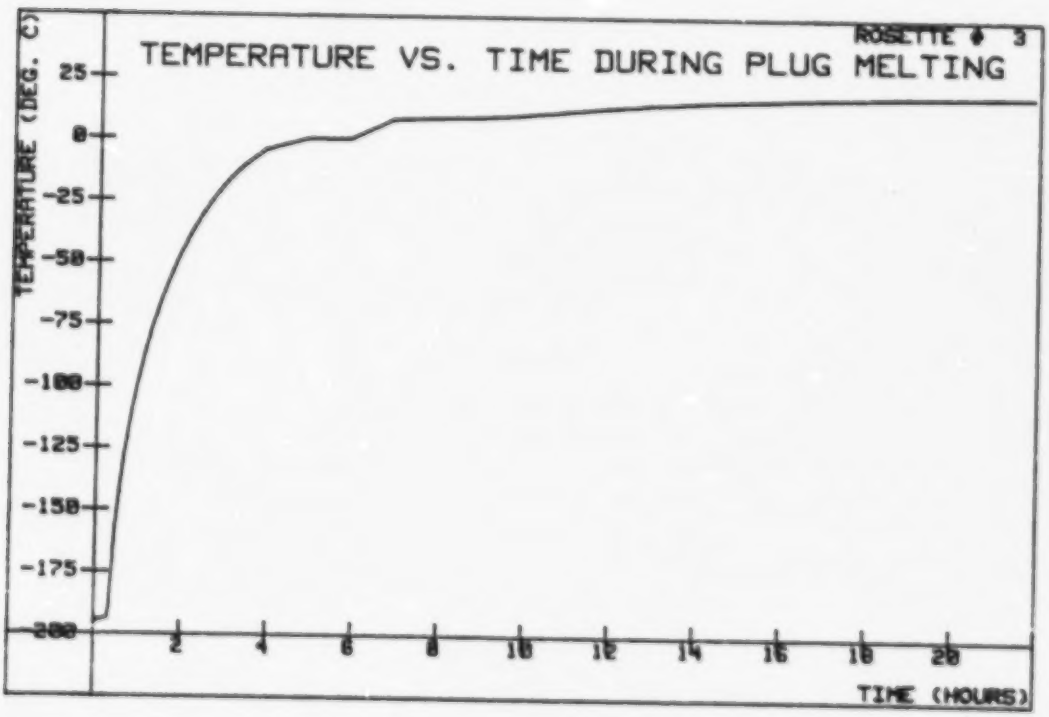

ROSETTE ♦ 1
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1/2
1/4
1/6
TIME (HOURS)

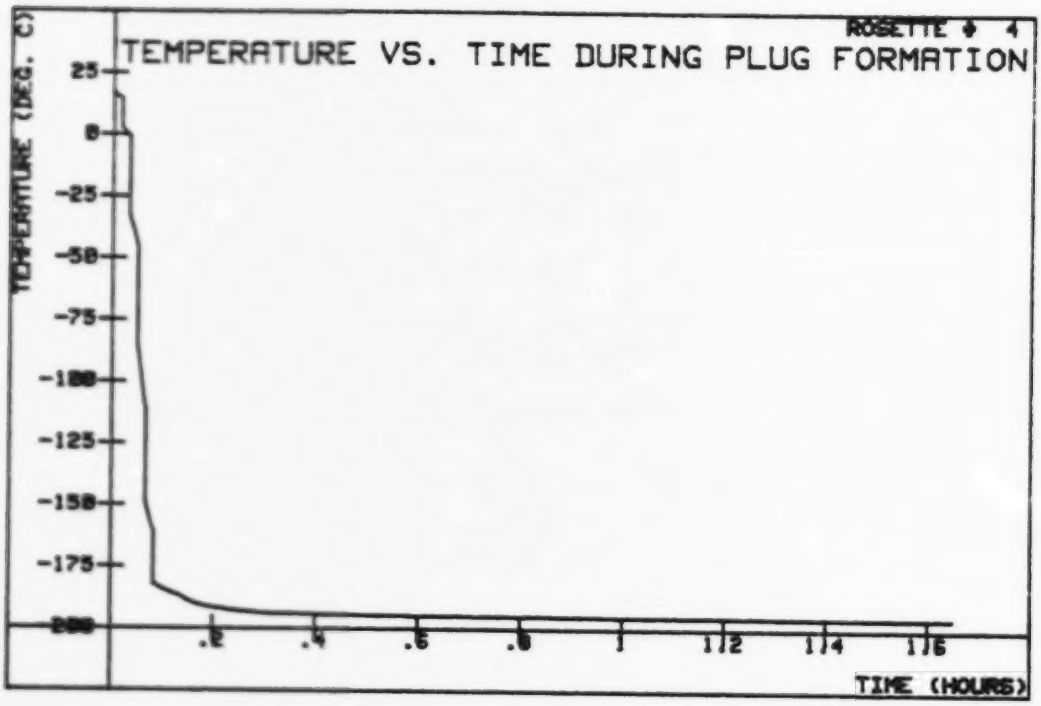

ROSETTE ♦ 1
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

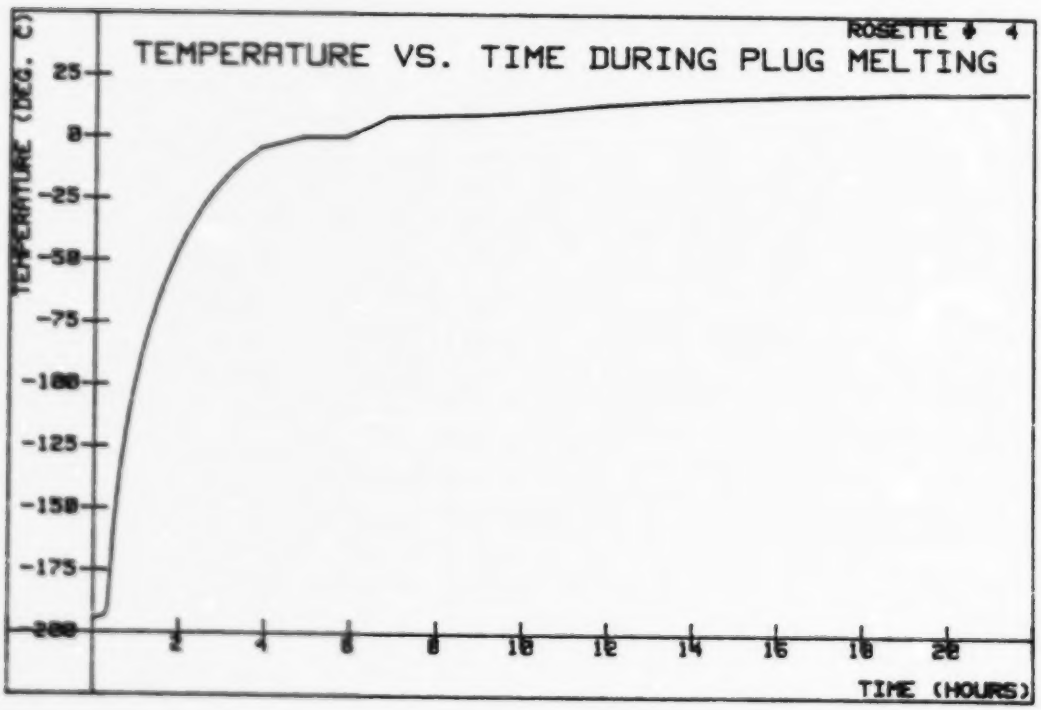

ROSETTE # 2
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1/2
1/4
1/6
TIME (HOURS)

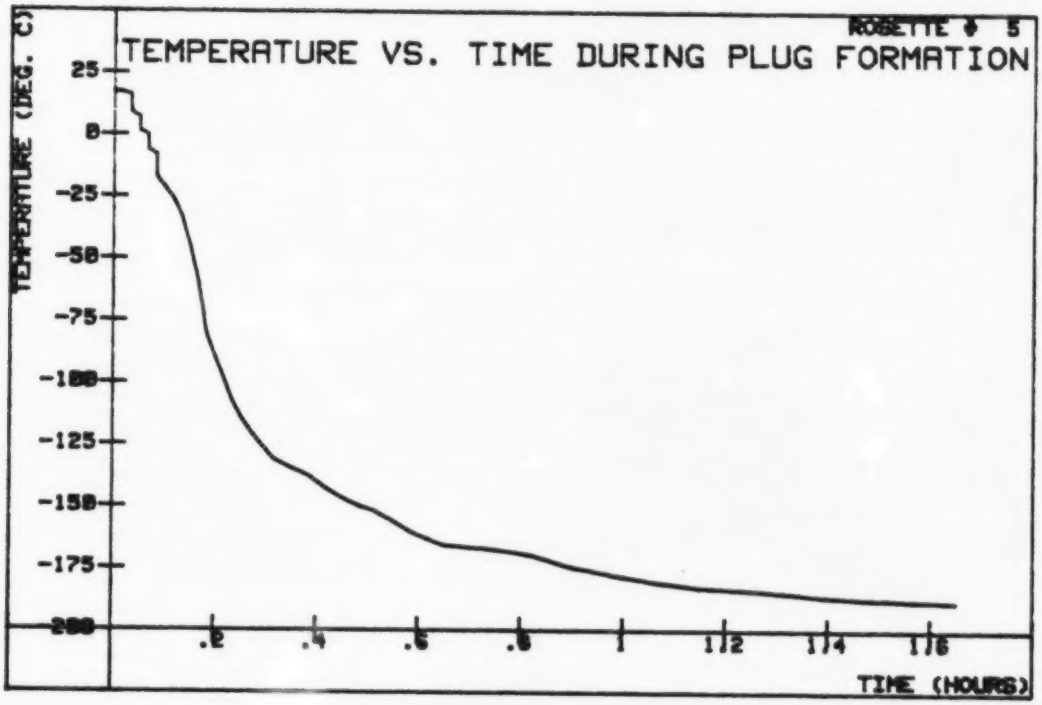

ROSETTE # 2
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

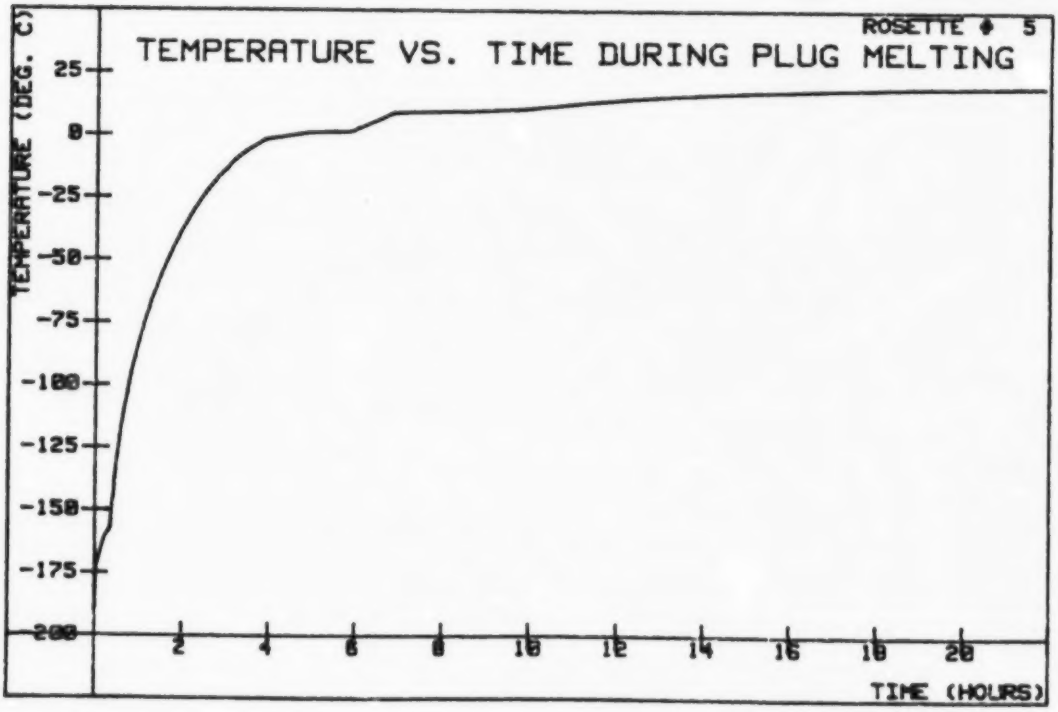

TEMPERATURE VS. TIME DURING PLUG FORMATION
ROSETTE # 3
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1/2
1/4
1/8
TIME (HOURS)

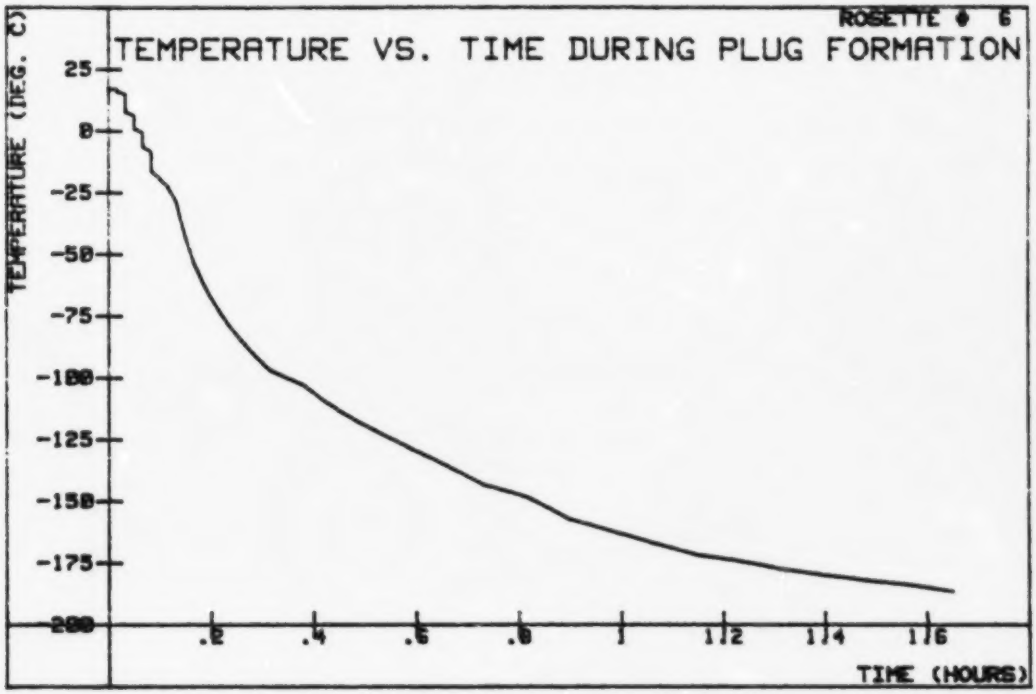

TEMPERATURE VS. TIME DURING PLUG MELTING
ROSETTE # 3
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

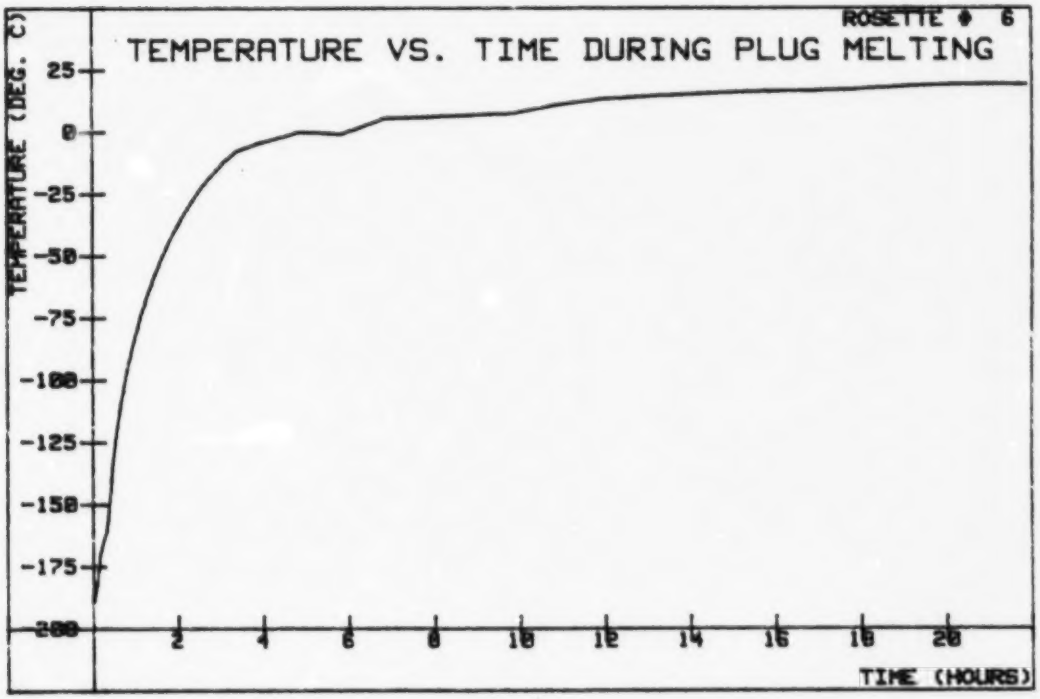

ROSETTE # 4
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/6
TIME (HOURS)

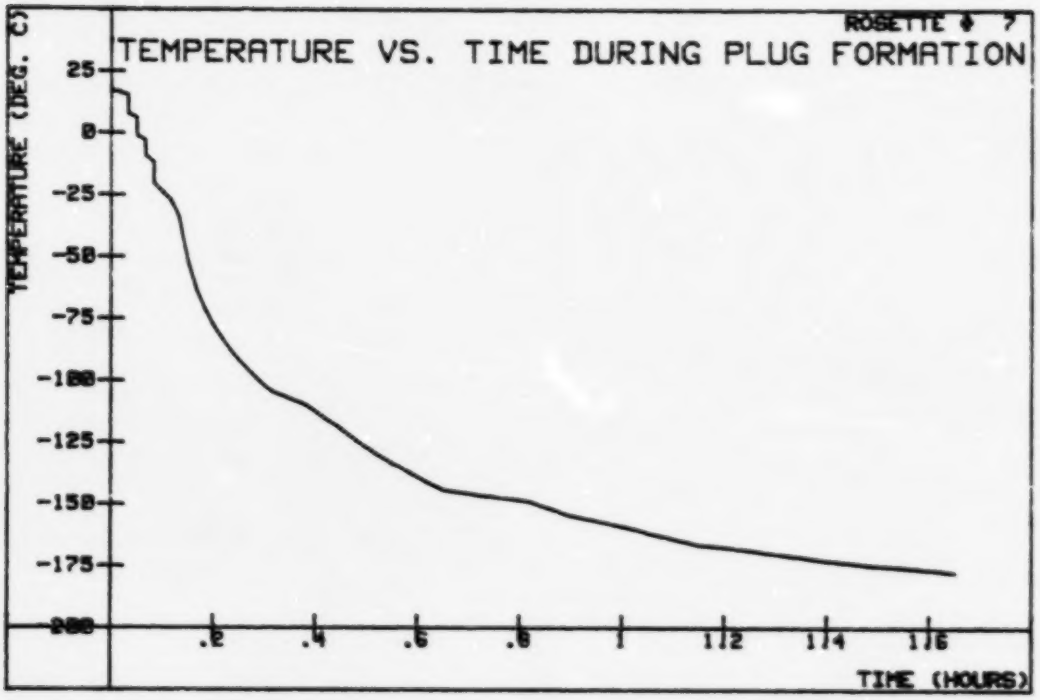

ROSETTE # 4
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

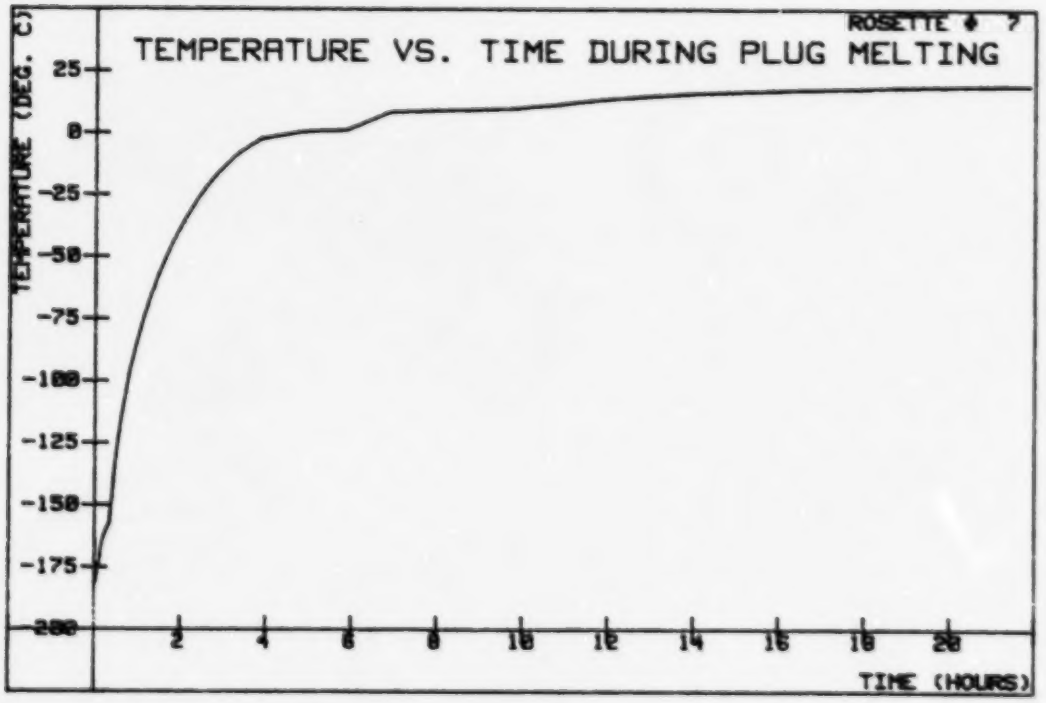

ROSETTE # 5
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1/2
1/4
1/8
TIME (HOURS)

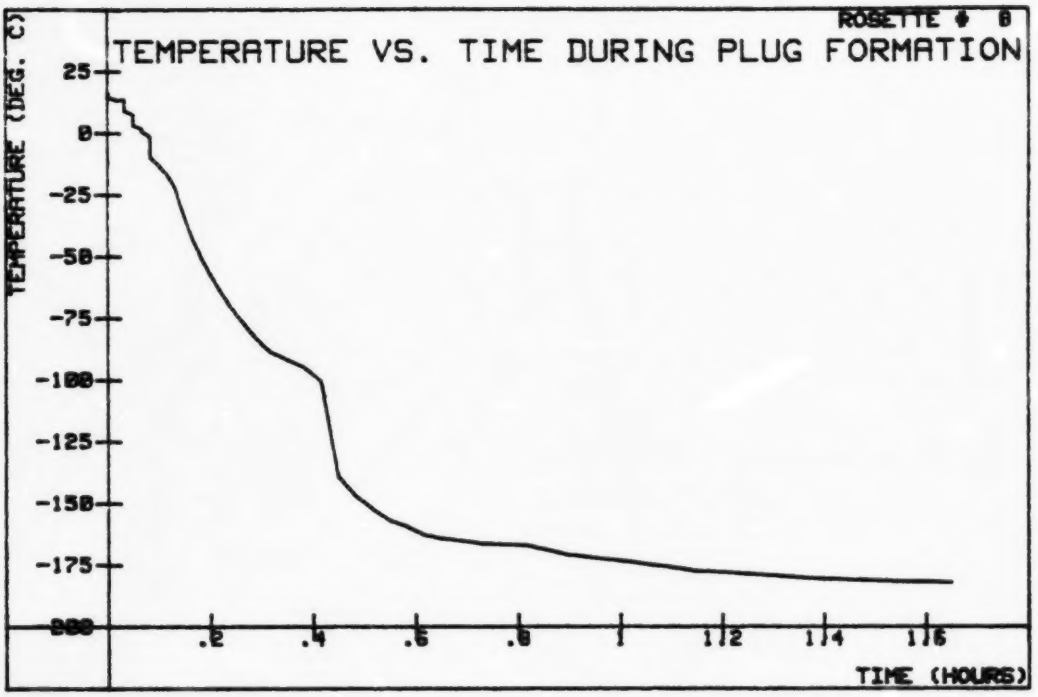

ROSETTE # 5
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

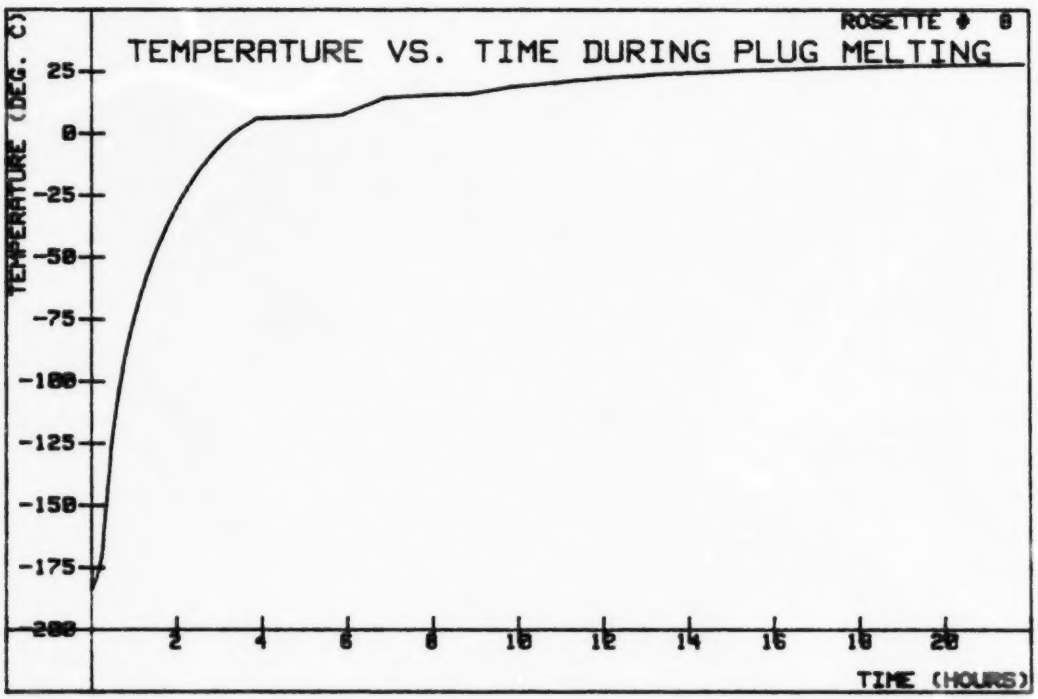

ROSETTE # 6
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1/2
1/4
1/6
TIME (HOURS)

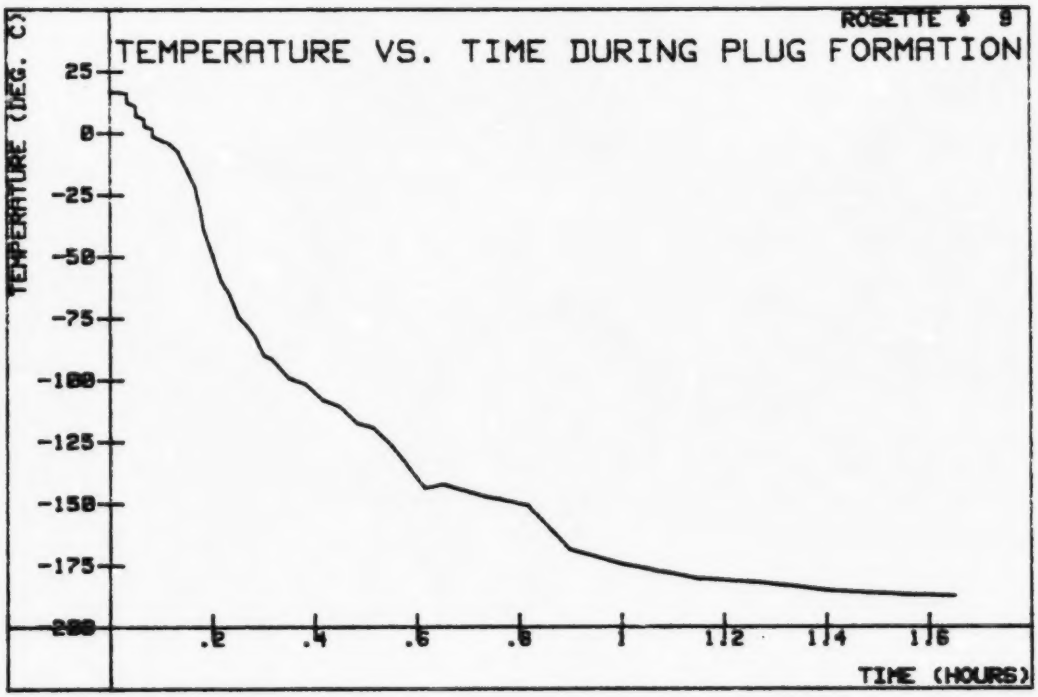

ROSETTE # 6
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

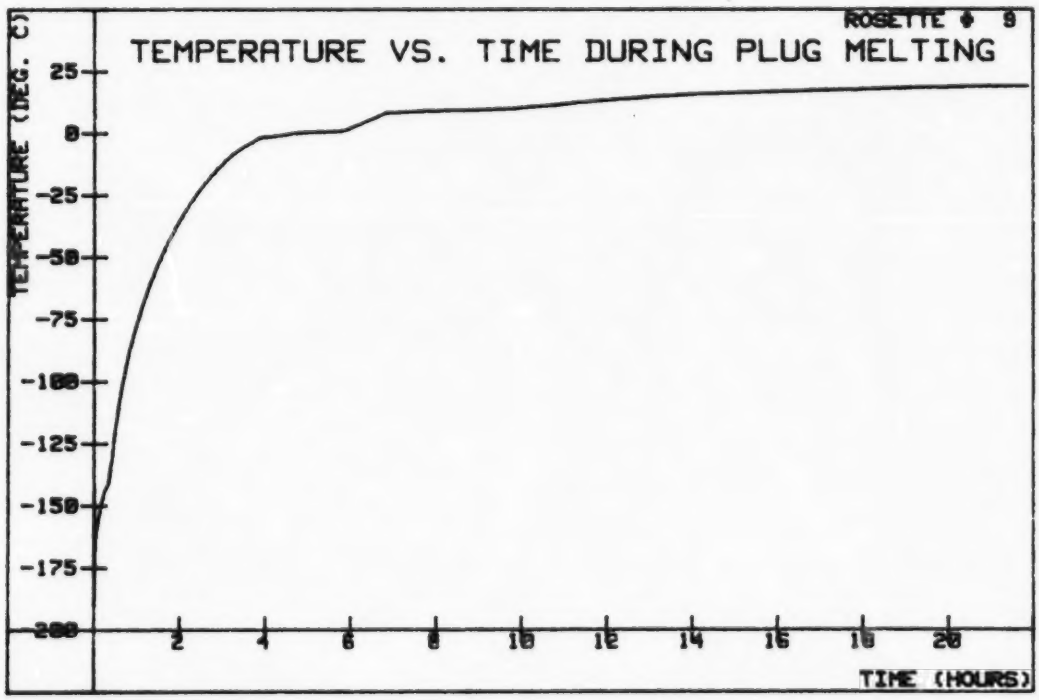

ROSETTE # 7
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/6
TIME (HOURS)

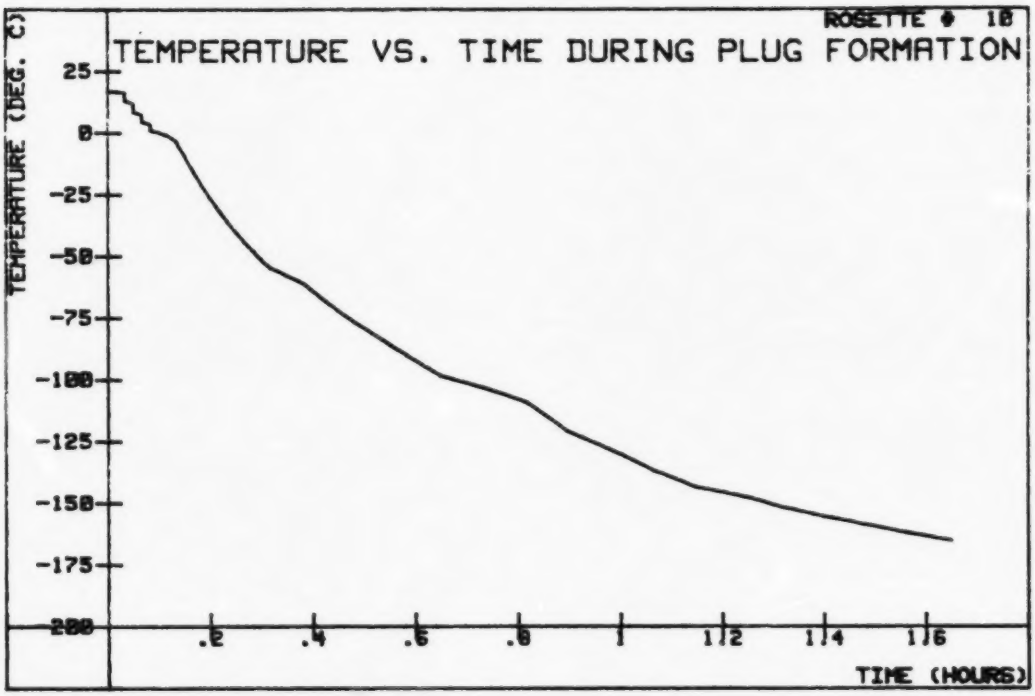

ROSETTE # 7
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

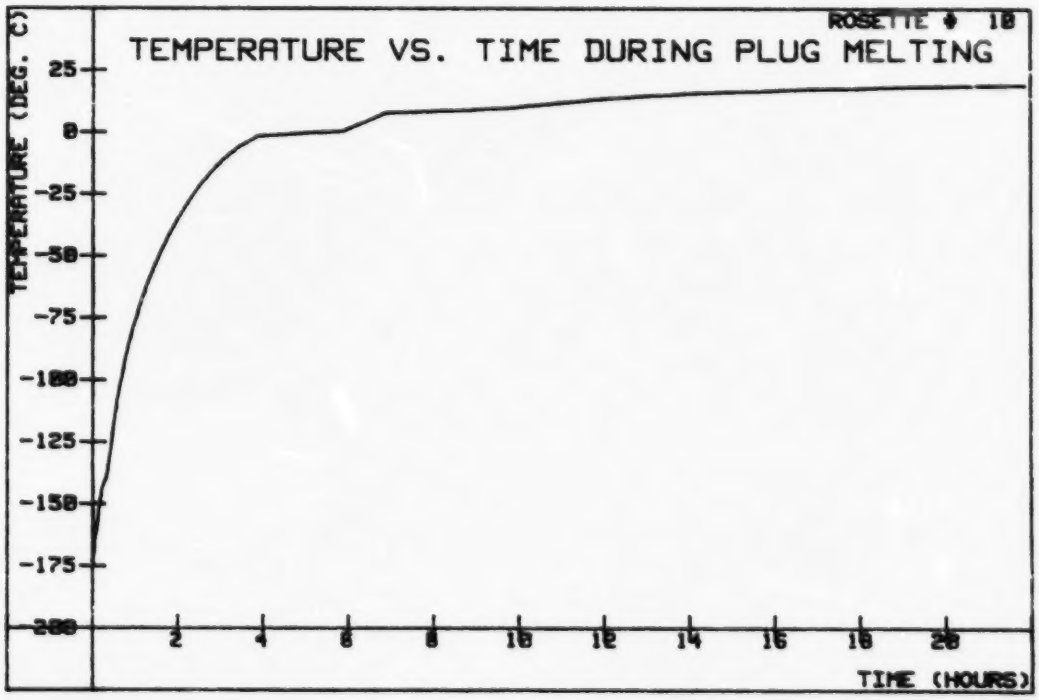

ROSETTE # 8
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/6
TIME (HOURS)

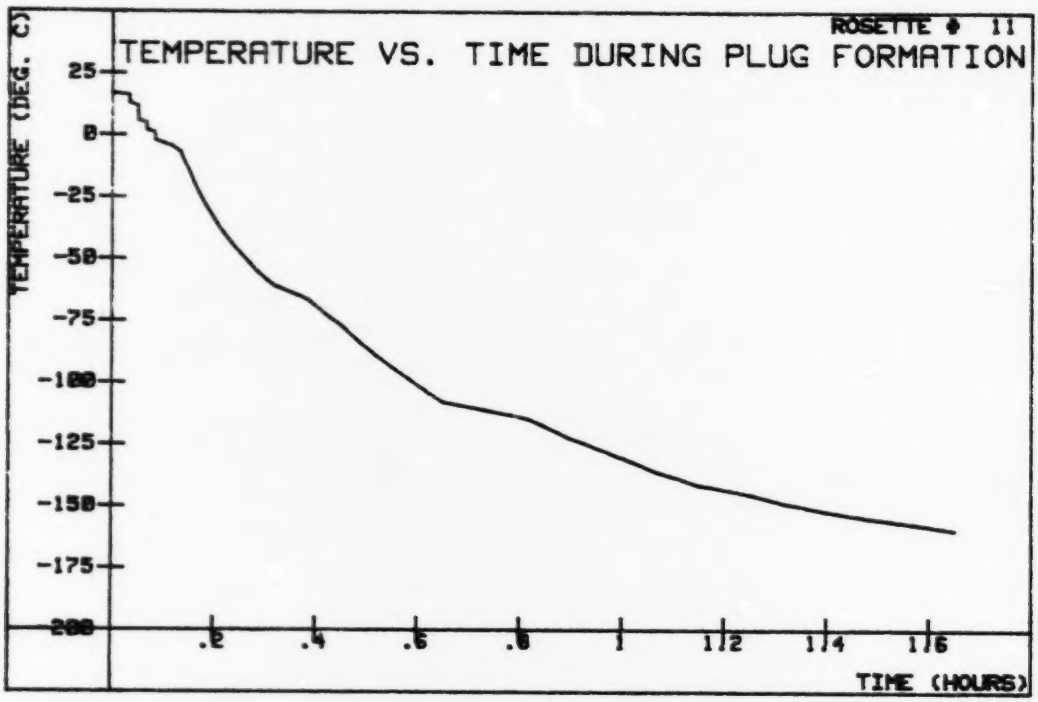

ROSETTE # 8
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

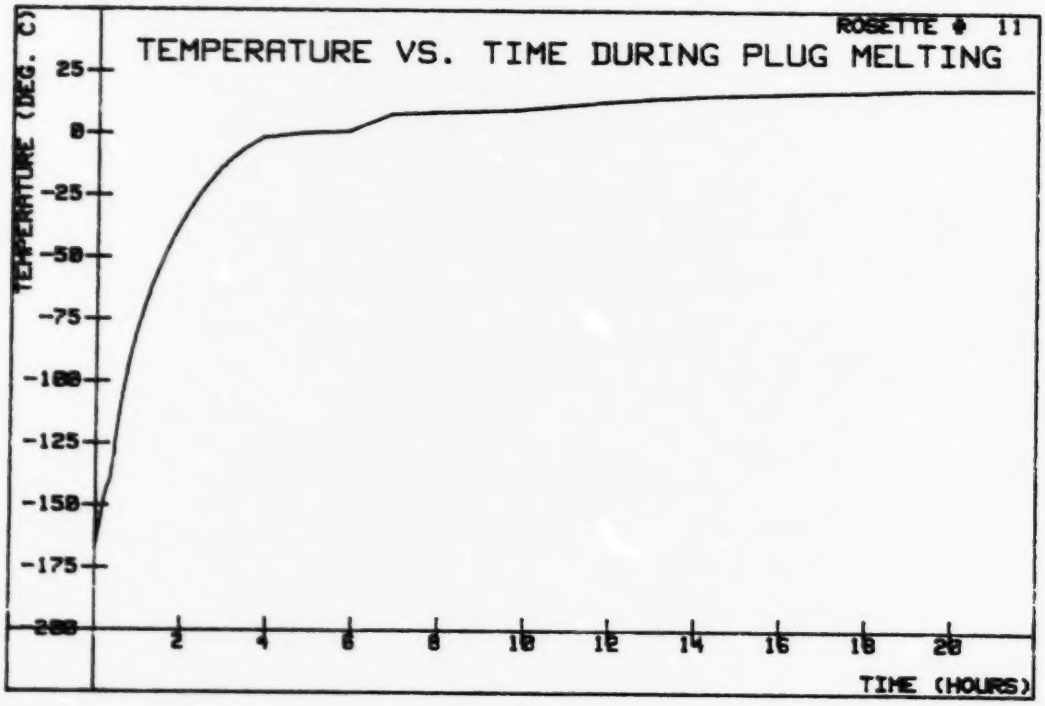

ROSETTE # 9
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

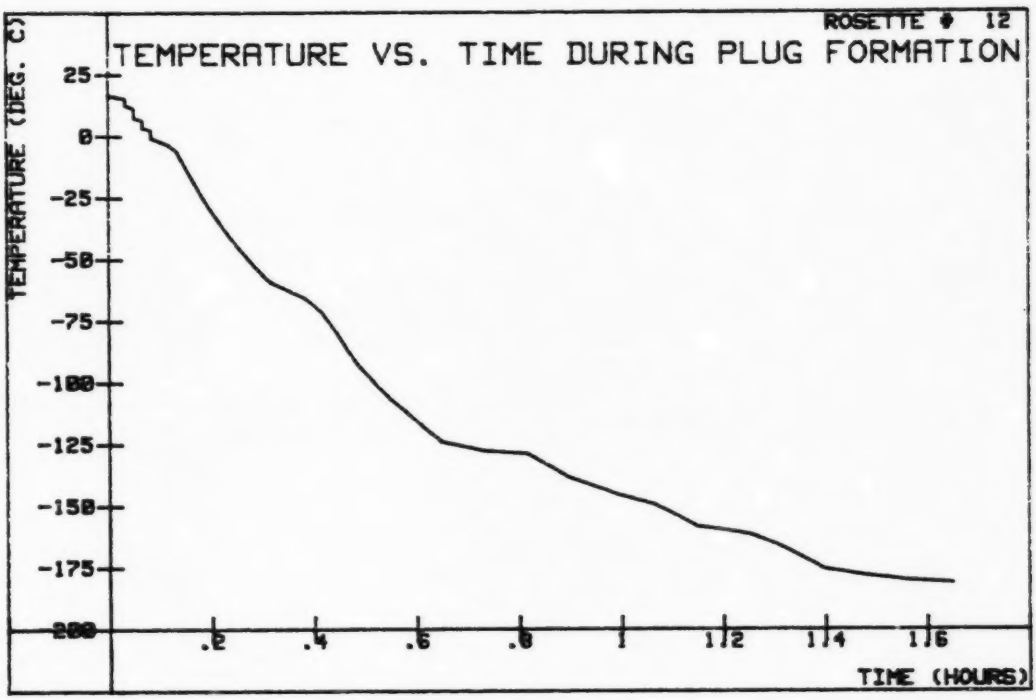

ROSETTE # 9
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

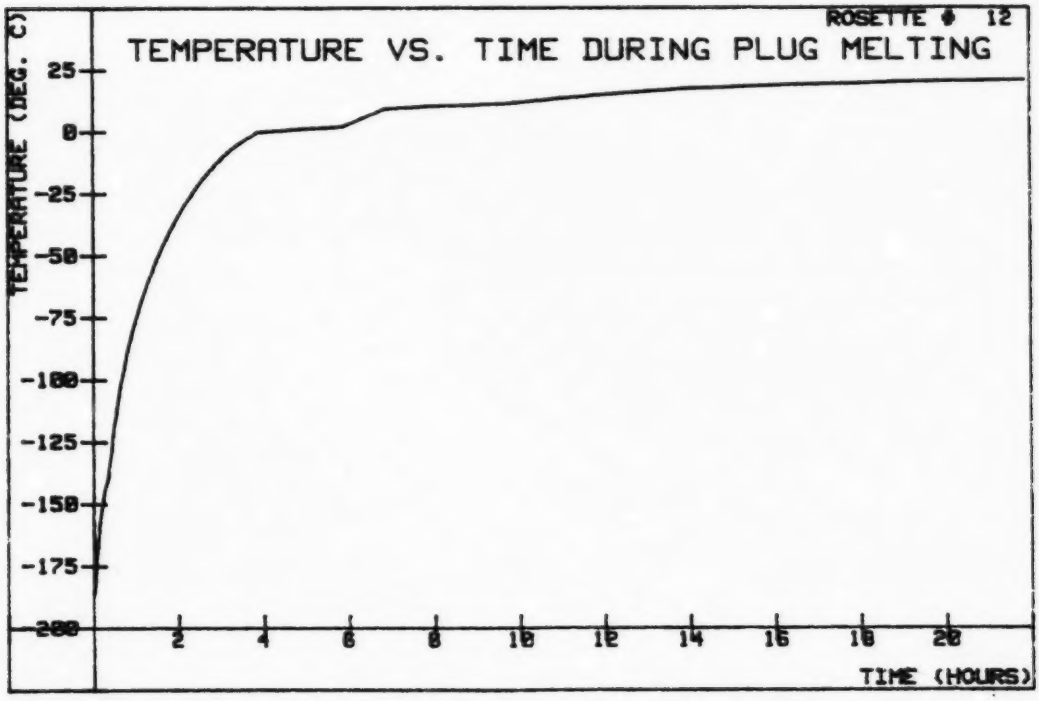

ROSETTE # 18
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1.2
1.4
1.6
TIME (HOURS)

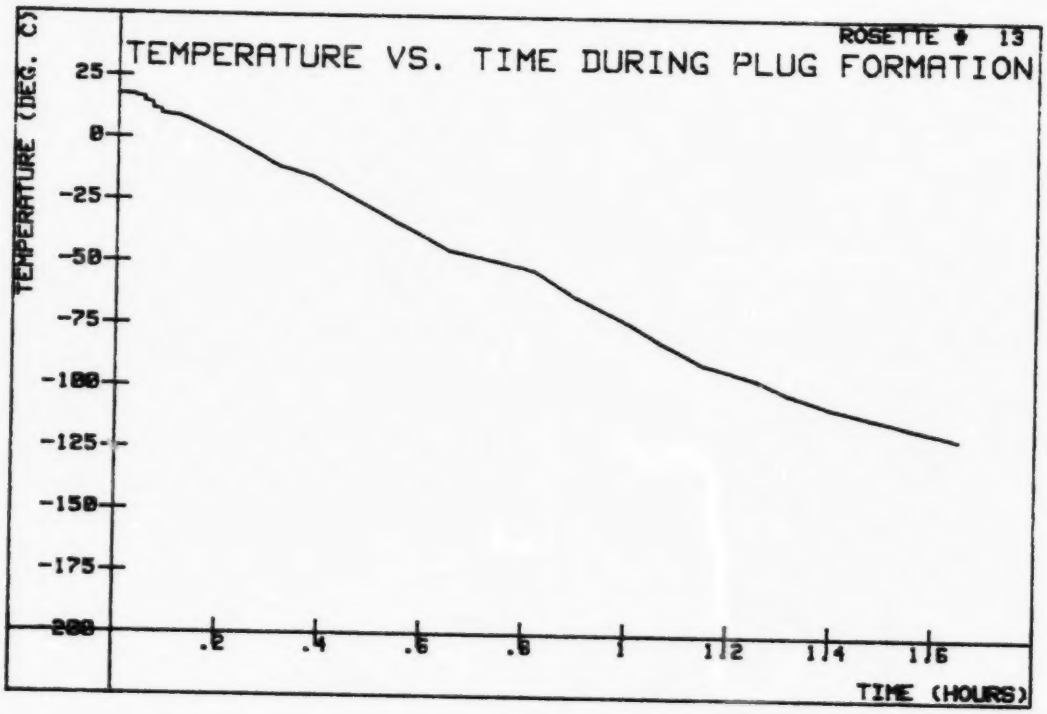

ROSETTE # 18
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

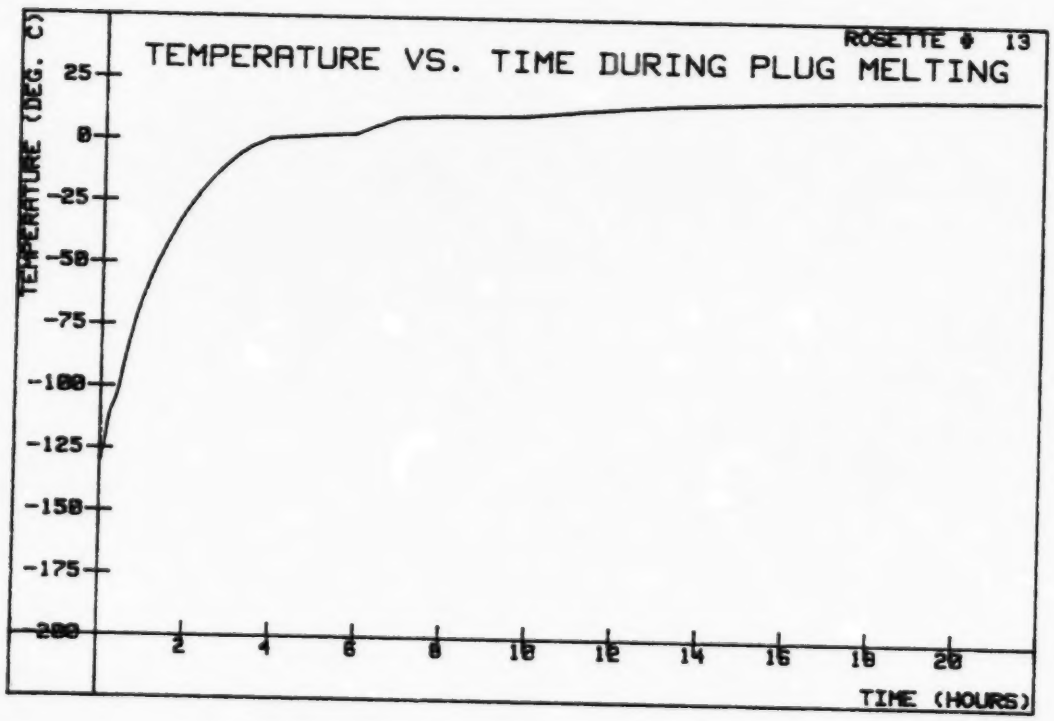

ROSETTE # 11
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1/2
1/4
1/6
TIME (HOURS)

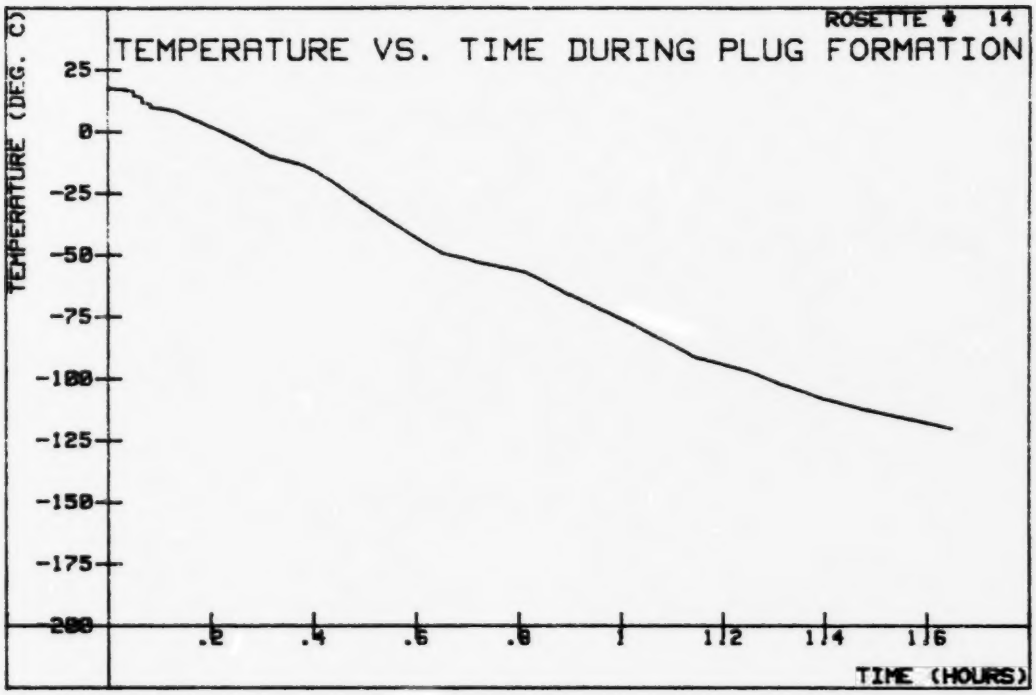

ROSETTE # 11
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

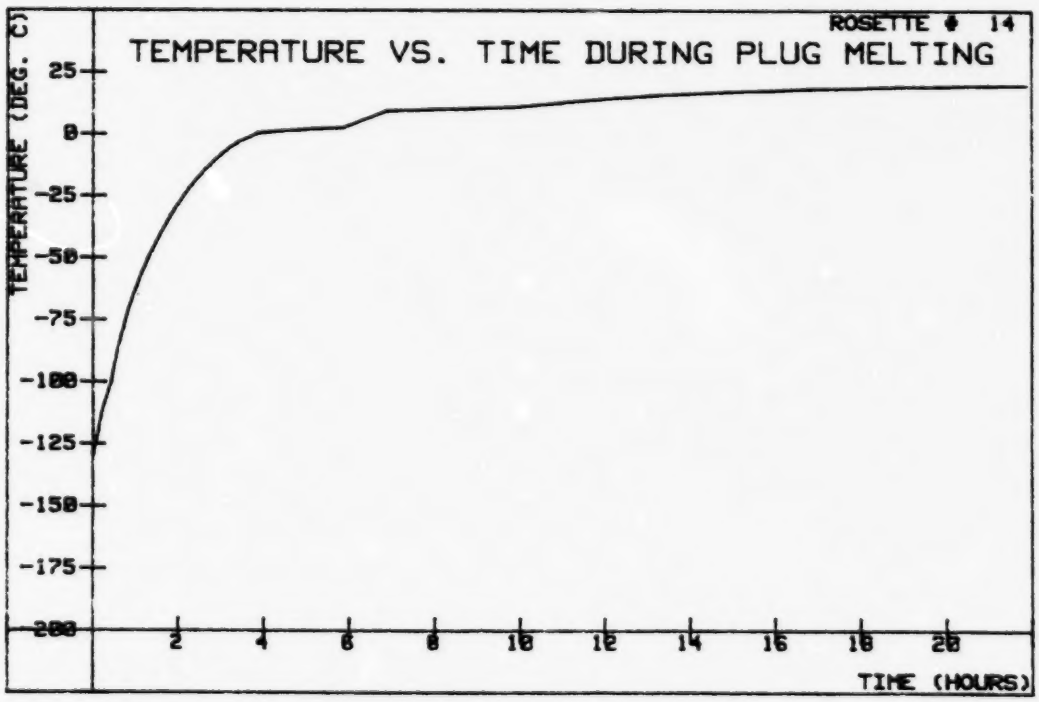

ROSETTE # 12
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/6
TIME (HOURS)

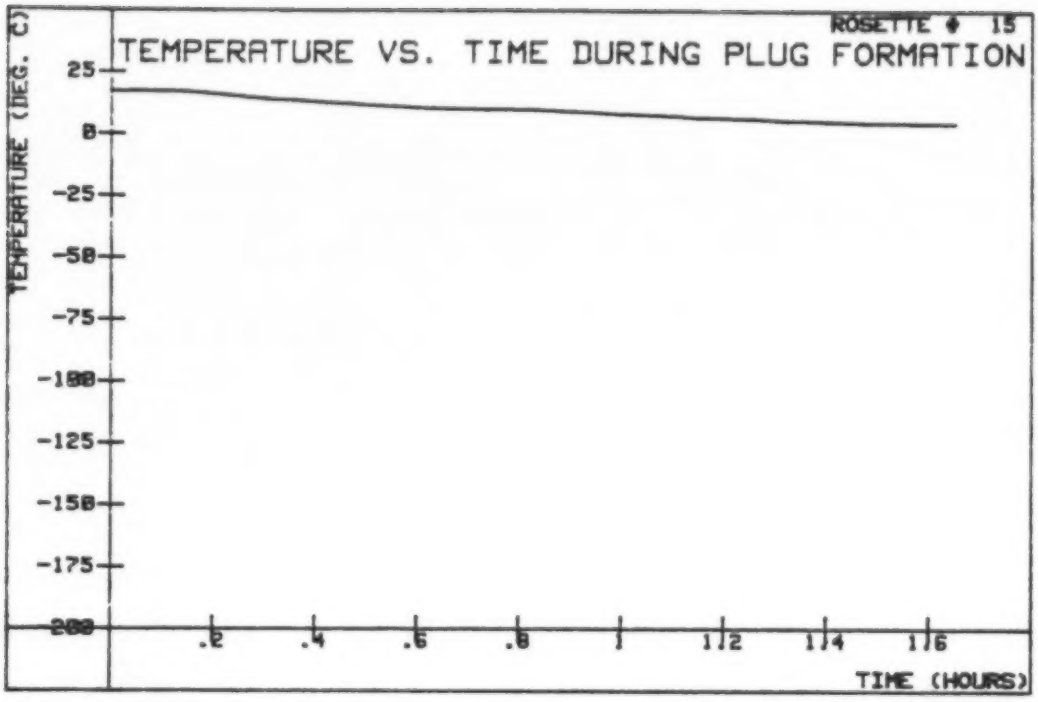

ROSETTE # 12
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)

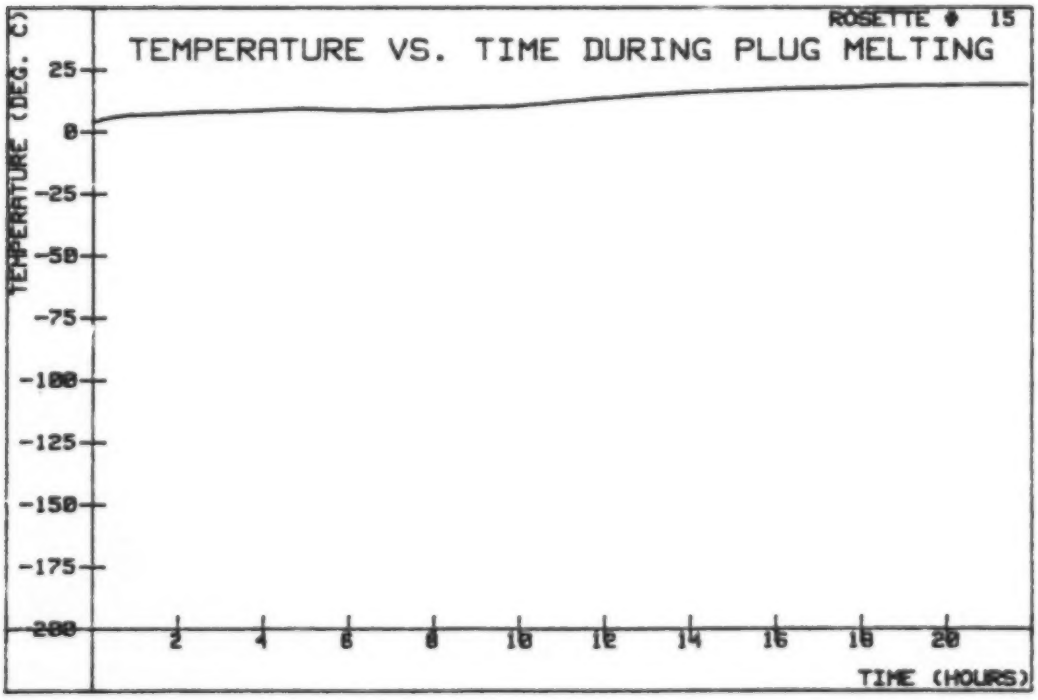

TEMPERATURE VS. TIME DURING PLUG FORMATION
ROSETTE # 13
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/6
TIME (HOURS)


TEMPERATURE VS. TIME DURING PLUG MELTING
ROSETTE # 13
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)


ROSETTE # 14
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/6
TIME (HOURS)


ROSETTE # 14
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)


ROSETTE # 15
TEMPERATURE VS. TIME DURING PLUG FORMATION
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
.2
.4
.6
.8
1
1 1/2
1 1/4
1 1/6
TIME (HOURS)


ROSETTE # 15
TEMPERATURE VS. TIME DURING PLUG MELTING
TEMPERATURE (DEG. C)
25
0
-25
-50
-75
-100
-125
-150
-175
-200
2
4
6
8
10
12
14
16
18
20
TIME (HOURS)